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Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments

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ABSTRACT

Heat island phenomenon rises the temperature of cities, increases the energy demand for cooling and deteriorates comfort conditions in the urban environment. To counterbalance the impact of the phenomenon, important mitigation techniques have been proposed and developed. Pavements present a very high fraction of the urban areas and contribute highly to the development of heat island in cities. The use of cool pavements presenting substantially lower surface temperature and reduced sensible heat flux to the atmosphere, appears to be one of the most important proposed mitigation solutions. The present paper investigates and describes the actual state of the art on the field of cool pavements. The main thermal and optical parameters defining the thermal performance of pavements are analyzed. Almost all of the developed technologies, where data and results are available, are considered while emphasis is given on the presentation of reflective and permeable/water retentive pavements. The main technological achievements on both fields are reviewed while existing applications are described and performance data are given when available. The existing results clearly show that the mitigation and cooling potential of cool pavements is very significant and can highly contribute to decrease temperature on the urban environment.

Contents

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1. Introduction

Heat island refers to the development of higher urban temperatures of an urban area compared to the temperatures of surrounding suburban and rural areas. The phenomenon is related to positive thermal balance created in the urban environment because of the increased heat gains like the high absorption of solar radiation and the anthropogenic heat, and the decreased thermal losses [1]. Uncontestably, heat island is the most documented phenomenon of climate change and is very well documented for various geographic areas of the planet [2,3]. In many cities the intensity of heat island may exceed several degrees while an important regional and temporal variability is observed [4]. Together with the phenomenon of global climate change are the main reasons for the observed important increase of urban temperatures [5–7]. The phenomenon is observed in specific areas of the cities presenting high density, and low environmental quality and results in a serious reduction of ambient thermal comfort levels and poor indoor thermal conditions [8–13]. As reported [14,15], between 1979 and 1998 the Center for Disease Control and Prevention in United States, estimated that exposure to excessive heat has resulted in about 7421 deaths in the US.

Heat island has an important impact on the energy consumption of buildings and increases their energy consumption for cooling purposes. Various studies have shown that the cooling energy consumption of buildings may be doubled because of the important increase of urban temperatures [16–25]. In parallel, because of the higher urban temperatures, the emission and generation of urban pollutants and in particular of tropospheric ozone increases considerably [24,26], while the ecological footprint of the cities suffering from heat island is growing seriously [25].

Counterbalancing the effects of urban heat island is a major priority for the scientific community. Several techniques have been proposed, developed and applied with quite high success [27]. Proposed mitigation techniques and technologies involve the use of the so called cool materials presenting a high reflectivity in the solar spectrum together with a high thermal emissivity value, able to amortize and dissipate solar and thermal energy [28–33], the development of smart materials presenting high optical and thermal performances [34–37], the use of green spaces in the urban environment involving appropriate landscaping and design of urban green modules [38,39], the use of appropriate heat sinks presenting low temperature to dissipate the excess ambient heat involving the use of the ground, ambient air and water [40–45], appropriate shading and solar control of urban surfaces [46,47], and the use of low temperature roofs in urban buildings, based either on the use of the previously mentioned cool materials on the roof surface (cool roof), or the installation of a plantation system on it (green or planted roof) [48–56].

The impact of pavements on the development of urban heat island is very important. Many recent studies have shown that paving surfaces play a very determinant role on the overall urban thermal balance [57–60]. Pavements cover a quite high percentage of the urban fabric and contribute highly to the development of heat island. Paved surfaces in Europe and USA, consist mainly of concrete and asphalt surfaces that present high surface temperatures during the summer period. Studies reported by Rose et al. [61], indicate that pavements in United States cover almost 29% of the urban fabric. Other studies reported in [62–65], for various US cities, show that paved surfaces including roads, sidewalks and parking areas cover between 29% and 39% when viewed above the urban canopy or 36–45% viewed under the canopy. As mentioned in [66], only parking lots in USA occupy 37.2 billion square meters covered by black asphalt. It is estimated that only in USA, about 166 billion dollars are necessary to improve the road surface in bridges and highways each year while more than half of the above amount is required for pavement preservation [67].

Decreasing the surface temperature of pavements may contribute highly to improve the thermal conditions in cities suffering from high urban temperatures. This can be achieved by replacement of conventional paving surfaces with new ones presenting much lower surface temperatures during the warm period, reconstruction, preservation and rehabilitation of the existing pavements to improve their thermal performance and shading of the paved surfaces to decrease absorption of solar radiation [68]. Advanced materials and surfaces, known as cool pavements, have been developed and are available for use in urban environments. Cool pavements are mainly based on the use of surfaces presenting a high albedo to solar radiation combined to a high thermal emissivity (reflective pavements), or are using the latent heat of water evaporation to decrease their surface and ambient temperature (water retention pavements). Both technologies are well developed and many commercial products are available to the market. In parallel, many large applications with cool pavements have been designed, constructed and evaluated with very promising and important results [69–77]. It is characteristic that in Japan the installed surface of cool pavements until 2009, was more than 800,000 m^2, while annual installations exceeded 270,000 m^2 [75].

The present paper aims to present and analyze the actual status of development of the main technologies associated to cool pavements. It evaluates the recent developments concerning reflective and permeable paving surfaces while it presents new ideas and applications beyond the above technologies. In parallel, it offers organized information on several case studies where cool pavements have been used in real scale projects and investigates the obtained results.

2. Pavements and urban climate

Pavements affect strongly the urban climate. Their thermal balance is determined by the amount of the absorbed solar radiation, the emitted infrared radiation, the heat transferred by convection to the atmospheric air, the heat stored into the mass of the material and the heat conducted to the ground. When latent heat phenomena are present, evaporation or even condensation affect the thermal regime of the pavement surfaces as well, while the effect of rain and icing has to be considered as well. Anthropogenic heat, because of the road traffic may also affect the thermal balance of the materials [78]. Specific studies reported in [79] show that infrared radiation from pavements in Tokyo causes heating of the atmosphere which is about half the rate of energy consumption of commercial areas in the city. As concluded in [79,80], pavements are the major contributors to the development of urban heat island.

The thermal balance of pavements and its impact on urban climate is analyzed using experimental and computational simulation techniques. Experimental evaluation of the thermal regime of pavement surfaces may be performed either by using mesoscale remote sensing techniques or microscale measurement methods involving infrared thermography and conventional temperature monitoring. Mesoscale satellite based techniques have been extensively used to assess the surface temperature in urban areas [81–86]. Satellite based techniques provide a useful tool to understand the spatial distribution of urban surface temperatures and assess at an early phase the impact of pavement materials on urban heat islands, however they are associated with several constraints like the time limitations set by the orbit of the satellites, the resolution of the images and the problems associated to the interpretation of the images [81,87,88]. Microscale measurement techniques provide detailed information on the thermal conditions of the

studied areas and allow a deep understanding of the corresponding thermal processes. Most of the microscale experimental campaigns have been performed using infrared thermography or conventional temperature measurements using thermocouples. Accurate measurement of surface temperatures using infrared thermography requires the exact knowledge or estimation of the emissivity of the selected materials. Methods to estimate the emissivity of materials are presented in [89–91]. The use of thermocouples to measure surface temperatures is a well known and accurate technique provided that a very good contact is achieved between the surface and the sensors. Comparative measurements of the surface temperature of various pavement materials using both infrared thermography and conventional temperature sensors were performed in [81]. As reported, the temperature differences ranged between 0.2 and 5.6 K. The infrared thermography showed higher temperatures than the used thermocouple sensors. The specific microscale techniques present a very high degree of accuracy and can provide instantaneous results and information on the diurnal variation of the temperature patterns; however they cannot provide a global visualization of the temperature distribution in a large area.

Computational simulation techniques were proposed and developed to predict and analyze the thermal performance of pavements. Models are able to investigate the specific thermal phenomena which may not be measured in a direct way. Several models were proposed using analytical or numerical techniques [92–99], with a variable degree of complexity. Most of the models claim a very good agreement with experimental data.

2.1. The role of the albedo

The amount of solar radiation absorbed or reflected is determined by the spectral and broadband absorptivity or reflectivity of the specific material. Data on the specific reflectivity of materials used for pavements and roads is reported in [100]. In general, the value of the reflectivity is determined by the color of the material and its roughness. Light colors present a lower absorptivity to the visual spectrum of solar radiation, while, the specific absorptivity to the infrared part of the radiation is quite independent of the perceived color. Absorptivity of solar radiation is also affected by the roughness of the surface. As reported in [101], where different pavement materials have been comparatively measured, tiles with smooth and flat surface were cooler than the tiles with rough and anaglyph surface.

Numerous studies have been performed to correlate the impact of the color of pavement materials on their surface temperature and sensible heat released. In [101], several types of commercial pavements were comparatively tested during summer. As reported the maximum surface temperature difference between black granites and white marbles reached values close to 19 °C, while significant temperature differences were measured between pavement types of different color. In [102], the surface temperature of different color thin layer asphaltic materials exposed to solar radiation was measured. Off white asphalt presenting an albedo to the visible part close to 0.45, was found to present almost 12 K lower maximum surface temperature than black asphalt having an albedo close to 0.03. In parallel, yellow, beige, green and red asphalt materials with albedos in the visual spectra of 0.26, 0.31, 0.10 and 0.11 presented 9.0, 7.0, 5.0 and 4.0 K lower maximum surface temperature than the black asphalt respectively. It is evident that the specific reflectivity value of the materials in the near infrared part of the spectrum affected almost equally the surface temperature. Measurements performed in street canyons [103,104], show that the surface temperature of black asphalt during summer reached temperatures close to 65 °C, the temperature of gray stone was 48 °C, while the surface temperature of shaded and non-shaded gray color cement pavements were around 30 and 60 °C, respectively. In another study [105], summer measurements performed in painted streets with an albedo of 0.55 against unpainted streets with albedo close to 0.15, showed that high albedo streets presented almost 11 K lower ambient temperature. The sensible transport and emissions measurements from asphalt pavements and bare soil are reported in [79]. Asphalt pavements contributed an additional 200 W/m^2 in sensible transport and emitted plus 150 W/m^2 in infrared radiation compared to the bare soil. Other measurements reported in [106], show that white elastomeric coatings with albedo of 0.72, were 45 K cooler than black coatings having an albedo of 0.08. A comparative assessment of different pavement materials used in the urban environment of Athens, Greece, was performed using satellite remote sensing techniques during the hot summer period, and is reported in [107]. The surface temperature of asphalt was measured to range between 77.6 and 81.8 °C, of concrete between 56.2 and 78.6 °C, of marble 48.6–67.3 °C and of stone between 47.5 and 75.1 °C. Comparative measurements of various pavement materials during the summer period is reported in [81]. In particular, conventional graded hot mix asphalt, asphalt rubber chip seal, gap graded asphalt rubber mixture, plain concrete pavement sections and plain concrete sections modified with the use of crumb rubber, were measured. It is found that the gap graded asphalt rubber concrete presented the highest surface temperature (67.8 °C), and the lowest albedo (0.12). The pavement made of concrete section had the highest albedo (0.48), and a surface temperature close to 51.8 °C. It is characteristic that the surface temperature of thick asphalt rubber was close to 66.7 °C for an albedo of 0.13 and was reduced to 51.1 °C when the albedo increased to 0.26 by adding some white paint. A sensitivity analysis regarding the impact of the albedo on the maximum and minimum surface temperature of various pavement materials is reported in [99]. It was found that materials with albedos close to 0.1 and 0.5 had surface temperatures close to 71 °C and 53 °C, respectively, while the corresponding minimum surface temperatures were 67 °C and 60 °C. Research reported in [108], shows that pavements presenting albedos of 0.05, 0.15 and 0.35 had a surface temperature equal to 50.5, 46.1 and 32.2 °C respectively.

Serious research efforts to increase the reflectively of the paving materials is carried out and reported. Technological developments aimed at two different directions: (a) to increase the albedo of light colored or white pavements, by increasing their spectral reflectance in the visible part of the solar radiation, and (b) to increase the spectral reflectivity of colored materials in the near infrared part of the spectrum. A review of the existing recent developments is given in the following sections.

2.2. The role of emissivity

Materials emit long wave radiation as a function of their temperature and emissivity. High emissivity values correspond to good emitters of long wave radiation and can readily release the absorbed energy. Simulation of the emitted thermal radiation from pavements in California showed that the net infrared radiation balance varied between 60 and 120 W/m^2 as a function of the surface temperature, [92]. Similar measurements reported in [79], show that the maximum upward infrared radiation over asphalt and normal color concrete was around 550 W/m^2, while the net infrared radiation balance varied between 0.0 and 80 W/m^2. Several studies were performed to understand the impact of the emissivity on the thermal performance of materials used in the urban environment. Measurement of the surface temperature of various highly reflective paving materials [109], has concluded that emissivity is the most important factor affecting the surface temperature of the materials during the night period. It is reported

that a very good correlation between the average nocturnal surface temperature and the corresponding material emissivity has been found. Materials having an emissivity of 0.93 presented a nighttime surface temperature depression of 5 K, compared to other materials with emissivity close to 0.35. Several other studies have highlighted the role of emissivity on the thermal performance of materials or even urban structures. A sensitivity analysis performed in [99] regarding the role of emissivity on the maximum and minimum surface temperature of various pavement materials has shown that when the emissivity value increases from 0.7 to 1.0 the maximum and minimum surface temperatures decrease by 5.0 K and 8.5 K, respectively.

In [110], the combined impact of surface reflectivity and emissivity of building materials was assessed using simulation techniques. It is reported that the role of emissivity is quite important when the reflectivity of the materials is reduced while, for high albedo values, the relative increase of the emissivity offers minor advantages regarding the cooling load of buildings. Simulation results reported in [111], regarding the optical and thermophysical characteristics of paving materials concluded that both the albedo and emissivity of the materials have the highest positive impact on the surface temperature of the studied materials. The impact of emissivity on the urban heat island is also studied in [112]. Simulations have shown that the role of emissivity on the heat island intensity during the night is quite minor. When the emissivity increased from 0.85 to 1.0, the temperature difference between the urban and rural environment varied by 0.4 K, and just for very narrow canyons.

2.3. The role of heat convection

Heat transfer by convection to and from the pavements surface is a function of the temperature difference between the ambient air and the surface of the pavement as well as of the heat transfer coefficient (h_{conv}). Heat convection may be free or forced or both, depending on the wind speed velocity and temperature difference. According to Jiji [113], the free convection coefficient over a flat plate is close to 5.9 W/m^2/K. For laminar air flow and for wind speeds not exceeding 2 m/s, the heat transfer coefficient may be calculated according to Çengel [114], while for higher wind speeds the formula proposed in [93], may be used. Simulation of the heat transferred by convection from the pavements to the ambient air for Californian cities during the summer period has shown that it varies between 0.0 and 125 W/m^2, and is a function of the temperature difference between the materials and the ambient air. Measurements over asphalt and concrete surfaces, reported in [79], show that the maximum convective transfer during the hottest time of the day was 350 and 200 W/m^2 respectively [79].

2.4. The role of other thermal parameters

Thermal conductivity and thermal capacitance are the main additional parameters that affect the thermal performance of pavements. The thermal characteristics of pavements and in particular of concrete are well documented [115–117]. Increased thermal conductivity of paving surfaces contributes to transfer faster the heat from the pavements to the ground and vice versa. Thus, during daytime, when the temperature of the pavements is higher than the temperature of the ground, heat is transferred to it, while during nighttime the adverse flow is observed. As a matter of fact, materials with higher conductivity present much lower average maximum and higher average minimum temperatures. Simulations performed in [99], to investigate the impact of thermal conductivity on the pavements surface have shown that when conductivity increases from 0.60 to 2.60 W/m/K, the average maximum surface temperature decreases by 7 K, while the average minimum temperature increases by 4.5 K. In another study [98,118], under much lower solar radiation and pavements surface temperature, simulations carried out have concluded that the role of conductivity is marginal for the pavement temperature near its surface.

The thermal capacity of the paving materials has a similar impact on the maximum and minimum surface temperatures like the thermal conductivity. High thermal capacity decreases the average maximum surface but at the same time increases the average minimum one. Simulations reported in [99], aiming to investigate the impact of the thermal capacity, have shown that when its value increases from 1.40 to 2.80×10^6 J m^{-3} °C^{-1}, the average maximum temperature decreases by almost 5 K, while the corresponding minimum temperature determines at large its temperature.

2.5. The impact of permeability

In permeable pavements, water passes to the soil through the materials voids/pores. It evaporates when the temperature of the material increases, contributing towards a lower pavement surface. The degree of evaporation is a function of the moisture content in the material and the atmosphere and depends highly on the temperature of the material. Higher moisture contents and increased watering may keep the surface of the pavements cooler [119]. Experiments reported in [120], have shown that dry permeable pavements present a higher surface temperature than the non-permeable equivalents [120]. Other experimental investigations [121], have shown that there is no correlation between the surface temperature and the permeability of the water retentive concrete blocks. Permeable pavements are more suitable for warm and humid climates where rain water is mainly used to cool down the surface of the pavements. Waste water may be used as the evaporative source as well. For dry climates where the availability of water is a problem, permeable pavements may not a suitable solution.

3. Improving the thermal performance of pavements

Effective mitigation of the impact of pavements on urban heat island necessitates a serious reduction of the sensible heat flux released to the atmosphere by the paving surfaces. This is equivalent to the reduction of their surface temperature during the day and night period. Paving materials presenting a relatively reduced surface temperature are known as cool pavements.

Reduction of the surface temperature of pavements may be achieved by employing some of the following techniques:

(a) To increase the albedo of the paving surfaces in order to absorb less solar radiation (reflective pavements). Most of the existing techniques apply to asphalt, concrete and other types of pavements. Existing techniques to increase the albedo of pavements include [122–125,108]: The use of conventional cement concrete pavement, the use of concrete additives like slag cement and fly ash, the application of white topping and ultra thin white topping techniques, the use of roller compacted concrete pavement, the use of light aggregates in asphalt concrete surfaces, the use of chip or sand seals with light aggregates, the application of color pigments and seals and the use of colorless and reflective synthetic binders, the painting of the surfaces with a light color using or not microsurfacing techniques, the use of sand/shot blasting and abrading binder surfaces, resin based pavements, etc. Some of the techniques are appropriate for new pavements while other for pavement rehabilitation and maintenance.

(b) To increase the permeability of the surfaces, in vegetated and non-vegetated pavements, in order to decrease their surface temperatures through evaporation processes. These types of pavements are known as permeable, porous, pervious or water retaining materials. As stated in [126], the words previous and permeable are synonymous and signify that water can flow through the material through a series of pores or connected holes. In porous materials holes are available in the material mass but are not necessarily connected. In general, permeable, porous or pervious pavements present a lower albedo than the impermeable equivalents, and higher convective fluxes to the atmosphere because of their higher effective surface area created by the increased void content [120]. Non-vegetated permeable pavements include [122–125,108], porous or rubberized asphalt, porous and pervious concrete, permeable interlocking concrete pavers, concrete and plastic grid pavers filled with gravels [126]. Vegetated permeable pavements provide cooling through evapotranspiration. It includes grass pavers, reinforced turf and concrete grid pavers use lattices of different types that allow grass to grow in the interstices.
(c) To increase the thermal storage capacity of the surfaces by adding ingredients of high thermal capacitance or materials of latent heat storage. Common materials used in pavements present a high thermal capacitance and is quite difficult to increase it further. However, addition of latent heat storage materials in the mass of the pavements, contribute to reduce surface temperatures during daytime and decrease sensible heat release to the atmosphere.
(d) To use external mechanical systems in order to reduce the surface temperature of the paving materials. This includes among other, circulation of a fluid in the mass of the pavement to remove the excess heat [127] and circulation of underground water in the pavement mass [128].
(e) Provide efficient shading of the paved areas using natural or artificial solar control devices. Shaded surfaces present a much lower surface temperature as the absorbed direct solar radiation is seriously reduced. Solar shading devices may be natural like trees and green pergolas or artificial. Shading devices should allow infrared radiation emitted by the pavements to escape in the atmosphere to promote radiative cooling of the pavements surface.

In the following sections the state of the art of the previously described types of pavements is presented.

4. Reflective pavements

Increasing the albedo of pavements helps to decrease their surface temperature and reduce the amount of sensible heat released to the atmosphere. In parallel, it decreases the need for night lighting and increases the durability of the pavements [129]. Pavements consist mainly of aggregates bounded by a binder. Albedo may increase by either provide an appropriate surface coating, or aggregates of light color or a proper binder or a combination of the above [130].

4.1. Existing developments and commercial applications of reflective pavements

This section describes initially in a brief way the existing commercial technologies to improve the albedo of pavements while it put more of the emphasis on new R+D developments presented recently.

Increasing the albedo of pavements is a common practice applied by the pavements industry. There are several techniques commercially available and widely used to rise the albedo of concrete and asphalt pavements. In particular, in existing pavements, resurfacing takes place by using proper aggregates and binders which may be mixed or not. When these two components are not mixed before the application and the binder is first sprayed on the existing pavement, then the aggregates are placed on the top of it and pressed, the technique is known as chip or sand seal. Chip seal techniques decrease the surface temperature of asphalt roads by almost 9.0 K [131]. When the binder and the aggregates are mixed and then applied on the pavement, the techniques are known as ‘microsurfacing’, ‘fog coating’, ‘overlay’ or ‘slurry coating’, as a function of the binder and the used aggregate [130,132].

White topping of asphalt pavements are associated with the use of concrete overlays placed on the surface of the asphalt. Given that cement has a much higher albedo than asphalt concrete, white topping contribute to decrease the surface temperature of the asphalt pavement. It is pointed out that the albedo of new concrete varies between 0.35 and 0.4, of the old between 0.2 and 0.3 while the albedo of new asphalt is around 0.05–0.1 and 0.1–0.15 for aged asphalt [133]. White topping varies as a function of the thickness of the overlay. Conventional overlays have a thickness higher than 20 cm, while thin and ultra-thin wtitetoppings are between 10–20 cm and 5–10 cm respectively [134,135]. Repairing of asphalt pavements is also done by using a mixture of aggregates with an asphalt emulsion. When polymers are used in the slurry binders the procedure is called ‘microsurfacing’ [131]. Petroleum or tree based resin coatings are available for resurfacing of asphalt pavements. Coloring additives together with proper aggregates are also used to increase the albedo of the pavements. Measurements reported by the developers show a surface temperature decrease of about 12 K, compared to weathered asphalt. A comparative experimental testing of eight commercially available technologies for improving the albedo of asphalt pavements is reported in [68]. It is found that six of the technologies present an SRI value higher than 0.29 or greater

4.2. Current research direction on the field of reflective pavements

Apart of the commercially available reflective pavements, important research developments are carried out and reported aiming to develop high reflective pavements. Five technological approaches are developed and tested (Fig. 1). Table 1 reports the main characteristics and results of the five main current research directions. In particular:

(a) The use of white high reflective paints on the surface of the pavement. New generation white paints of new generation present a very high solar reflectivity that in many cases exceeds 90% [136]. Use of such paints could significantly decrease the surface temperature of the pavements and decrease sensible heat released to the atmosphere. The use of high reflective paints applied on the surface or the mass of the pavements is studied and results reported in [109,137]. In both cases the highly reflective paints are applied on the surface of concrete pavement tiles. Albedos in both cases ranged between 0.8 and 0.9. Experimental testing was performed during hot summer conditions and comparative results are reported against conventional white tiles. In particular, the thermal performance of 14 highly reflective white concrete pavement materials covered with reflective paints based on different types of technologies, were comparatively tested under hot summer conditions in [109]. The albedo of almost all tested materials was between 80% and 90%. The emissivity of the non-aluminum pigmented coatings was higher than 0.8, while for the aluminum based paints it varied between 0.3 and 0.4. It was found that the use of highly

reflective coatings reduces the daily surface temperature of a white concrete pavement under hot summer conditions by 4 K and by 2 K during the night. The specific tiles were warmer than the ambient air by only 2 K during the day and cooler by 5.9 K during the night. A clear correlation between the emissivity of the materials and the nocturnal surface temperature was found. Pavements covered with aluminum based paints presented a higher surface temperature than the other tiles. Aging of the used paints is found to play a very important role on the thermal performance of the pavements. It is reported that the acrylic elastomeric coatings was the coolest coating during the daytime period of the first month of the monitoring period, but became a lot warmer during the second and third month of the testing. Highly reflective white coatings ($\rho=0.88$), based on the use of calcium hydroxide were also prepared and tested against conventional white pavements ($\rho=0.76$), under summer conditions [137].

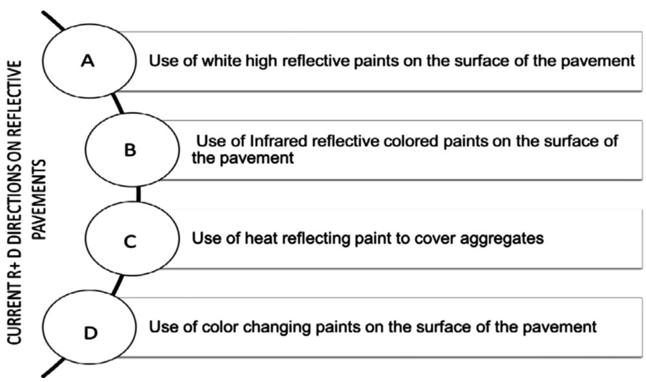

Fig. 1. Current research priorities on the field of reflective pavements.

The infrared emittance of the material was close to 0.85. Such a coating is inexpensive, environmentally friendly, permits the air to pass through while it presents high dirt pick up resistance. The main disadvantage of the materials is the effect of chalking. To face the problem, an acryl binder was used. It is reported that during the daytime the prototype reflective materials have lower surface temperatures ranging between 1 and 5 K, while during the night the difference was close to 1 K.

(b) Use of Infrared reflective colored paints on the surface of the pavement. When nonwhite pavement materials have to be employed, infrared reflective pigments may be used to increase their global albedo [136]. Such a pavement surface of any color, may reflect strongly in the near infrared part and thus present a much higher solar reflectivity than a conventional material of the same color [138,139]. Infrared reflective paints are used to modify the surface albedo of colored concrete and asphalt pavements by five research groups [102,140–143]. Infrared reflective paints were applied directly on the surface of concrete pavements in [136]. In [142,143], IR reflective paints were applied on the surface of asphalt together with hollow ceramic spheres to reduce the conductivity of the pavement. In [102], thin reflective asphaltic layers of different colors developed using infrared reflective pigments were applied on conventional ashalt pavements. In [140], ten prototype cool colored pavement materials using infrared reflective pigments were tested against conventional materials of the same color, under hot summer conditions. As reported, the reflective black material presented an albedo close to 0.27 and had a mean daily surface temperature almost 10 K lower, compared to the standard black, $\rho=0.05$. In parallel, the reflective blue had an albedo close to 0.33 and almost 4.5 K lower mean surface temperature compared to the conventional blue having a reflectivity of 0.18. In general, an

Table 1
Description of the existing technological trends on the field of reflective pavements.

No.	Description of the technology to Increase the Albedo	Technological details	Type of pavement	Final albedo achieved	Thermal benefits	Reference
1.	Use of white high reflective paints on the surface of the pavement	Use of 14 high reflectivity white paints placed on the surface of concrete tiles	Concrete	0.80–0.90	Reduce of the daily surface temperature of a white concrete pavement under hot summer conditions by 4 K and by 2 K during the night	[109]
		High reflectivity white paints based on the use of calcium hydroxide placed on the surface of concrete tiles	Concrete	0.76	Reduce of the daily surface temperature under hot summer conditions by 1–5 K and by 1 K during the night compared to a same color concrete pavement	[139]
2.	Use of Infrared reflective colored paints on the surface of the pavement	Use of ten infrared reflective paints of different color placed on the surface of concrete tiles	Concrete	0.27–0.70	Reduce of the daily surface temperature under hot summer conditions by 2–10 K compared to a same color concrete pavement	[143,144]
		Use of a dark infrared reflective paint placed on the surface of asphalt together with hollow ceramic particles on the mass of the pavement	Asphalt	0.46	Reduce of the daily surface temperature by 5 K compared to a same color concrete	[145]
		Use of a dark infrared reflective paint placed on surface of asphalt together with hollow ceramic particles	Asphalt	0.50	Reduce of the daily surface temperature of the pavement by 8–15 K and by 2 K during the night compared to conventional asphalt	[150]
		Five thin reflective layers of different colors using infrared reflective pigments for asphaltic pavements	Asphalt	0.27–0.55	Reduce of the daily surface temperature of the pavement by 16–24 K and by 2 K during the night, compared to conventional asphalt	[102]
3.	Use of heat reflecting paint to cover aggregates of the asphalt	Use of a reflecting paint to cover all aggregates of the asphalt	Asphalt	0.46–0.57	Reduce of the daily surface temperature of the pavement by 10.2–18.8 K, compared to conventional asphalt	[148]
		Use of a reflecting paint to cover the surface aggregates of the asphalt	Asphalt	0.25–0.6	Reduce of the daily surface temperature of the pavement by 6.8–20 K, compared to conventional asphalt	[149]
4.	Use of color changing paints on the surface of the pavement	Use of eleven thermochromic colors applied on the surface of concrete pavements	Concrete	Colored: 0.51–0.78 Colorless: 0.71–0.81	Reduce of the daily surface temperature of the pavement by 5.4–10 K, compared to conventional pavements	[34]
5.	Use of fly ash and slag as constituents of the concrete	When 70% of slag is used as cement replacement the mix presented an increased albedo	Concrete	0.58	Not available	[147]

almost linear relation was found between the mean surface temperature and the albedo of the materials. Much lower surface temperatures were measured also during the nighttime. Similar results are reported in [144].

The experimental testing of a commercially available pavement based on dark, low reflective color pigments mixed with infrared reflective pigments and fine hollow ceramic particles is reported in [142]. The experiment has taken place in Singapore. The albedo of the pavement was close to 0.46 and the emissivity 0.83 while the reflectivity in the near infrared was 0.81. It was found that the specific pavement presented up to 5 K lower surface temperature compared to conventional concrete pavements.

The use of colored reflective pavements, based on the use of inorganic infrared reflective pigments, is already commercialized in the United States. The albedo of the proposed pavements is around 0.45–0.55 [145–147]. As reported, the use of the pavements reduces surface temperatures by 11–22 K.

Thin layer asphalt pavements are developed by mixing colorless elastomeric asphalt binders with infrared reflective pigments and aggregates of special characteristics [102]. Five samples (green, red, yellow, beige and off white), were developed and tested under hot summer conditions against samples of conventional asphalt. The albedo of the thin asphalt layers ranges between 27% for the red and green samples and 55% for the off white sample. The reflectance of the conventional asphalt was measured around 4%. All samples presented a high absorptance in the UV range, while their reflectance in the infrared was high and between 39% and 56%. Thermal monitoring of the samples has shown that during the day all samples demonstrated a surface temperature that was higher than the ambient one, while during the nighttime the air temperature was always higher than that of the asphalt samples, mainly because of the high emissivity of the materials. The average daytime surface temperature of the samples ranged from 36 °C for the off white sample to 43.6 °C for the red one. The corresponding surface temperature of the conventional asphalt was close to 60 °C. The nighttime surface temperature of all the developed samples was almost 1–2 K lower than that of the conventional asphalt. Using CFD simulation techniques, it was estimated that the possible use of the specific asphalt pavements applied to roads may reduce the ambient temperature up to 5 K under low wind speed conditions.

(c) Use of heat reflecting paint to cover aggregates of the asphalt. The use of IR reflective paints to cover the aggregates used in asphaltic pavements is proposed and tested in [148,149]. In particular, the development and testing of four types of high albedo asphalt pavements is reported in [148]. The pavements are made using a heat reflecting paint that has coated each piece of aggregate, while in conventional reflective asphalt pavements the paint is applied only in the surface. The albedo of the pavements varied between 0.46 and 0.57. Monitoring showed that the developed pavements present a much lower surface temperature than a conventional drainage pavement, while temperature differences varied between 10.2 and 18.8 K. In parallel, a similar technology to prepare high albedo coatings for asphalt pavements was proposed and tested in [149]. The experiment taken place in Japan, during the summer period. It is reported that when the albedo of the pavement increased to 0.25 its surface temperature was almost 6.8 K lower than that of the conventional asphalt, while when the albedo increased to 0.6 the corresponding surface temperature decrease was close to 20 K. In a general way, it is found that when the albedo value increased by 0.1 the corresponding decrease of the surface temperature was close to 2.5 K.

(d) Use of color changing paints on the surface of the pavement. Color changing coatings to be applied on pavements were proposed by several authors [34,36,37]. In particular thermochromic coatings are able to respond thermally to the environment and change reversibly their color and reflectivity from lower to higher values, as temperature rises. Such type of pavements were developed and their thermal performance was tested [34], in comparison to highly reflective and common coatings. Eleven tiles of different color were developed and tested under hot summer conditions. The pavement coatings were developed using organic thermochromic pigments together with an appropriate pigment and other stabilizing components. The infrared emittance was very similar for all the tested pavements. Monitoring of their surface temperature has shown that the daily mean surface temperature of the thermochromic coatings range from 31.0 to 38.4 °C, from 34.4 to 45.2 °C for the infrared reflecting cool coatings and 36.4–48.5 °C for the common coatings. In all cases, the mean daily surface temperature of the thermochromic pavements was lower than that based on the use of infrared reflecting pigments and the common coatings. The nocturnal temperature of the three types of tested coatings was almost similar. Measurements of the spectral reflectivity of the thermochromic coatings, have shown that their maximum albedo increase from colored to colorless phase was 43%. The major problem of the thermochromic coating has to do with the rapid loss of their optical characteristics. Important research has been carried out to face the problem of ageing and the obtained results are very promising.

(e) Use of fly ash and slag as constituents of the concrete. The development of concrete surfaces presenting a higher albedo value is presented in [148]. In particular fly ash and slag are used as constituents for the preparation of the concrete. It is reported that when 70% of slag is used as cement replacement the mix presented an albedo of 0.582 which is 71% than the albedo of the conventional mix. Although the results are quite important, developments on this field are limited and may not be considered as a strong research direction.

4.3. Studies on the climatic potential of reflective pavements

The climatic potential of an increased urban albedo to fight heat island and decrease the temperature of the cities is investigated for several US cities. A review of the existing studies is given in [105], while the main characteristics and results are summarized in Table 2.

Almost all existing studies assume a global increase of the urban albedo considering different assumptions for the reflectivity of the pavements, roofs and walls. Almost all studies were performed using mesoscale simulation models and results refer to the combined impact of all considered options regarding the increase of the urban albedo.

Among the studies previously mentioned, three out of them have considered a specific scenario for pavements. In particular, a simulation study performed for Los Angeles [150], has considered that the albedo of pavements and roofs increases from 0.05 to 0.25, and from 0.15 to 0.25, respectively. It was calculated that the peak ambient temperature in the city may decrease by 1.5 K. A second study [151], carried out for various US cities, has considered that the albedo of pavements and roofs may increase by 0.15 and 0.25, respectively. It was calculated that the average expected decrease of the mean ambient temperature may range from 0.11 to 0.53 K, as a function of the characteristics of the various cities considered. Finally, a third numerical study carried out in Huston

Table 2
Characteristics of the existing studies on the thermal impact of a possible increase of urban albedo.

Ref.	City/country	Initial albedo	Final albedo	Reduction of maximum ambient temperature (K)
[154]	Fresno, USA		Increase of albedo of the city because of cool pavements by 0.02	Reduction of the average ambient temperature by 0.2 K
[154]	Fresno, USA		Increase of albedo of of the city because of cool pavements by 0.09	Reduction of the average ambient temperature by 0.8 K
[75]	Tokyo, Japan		Increase of the albedo by using cool pavements	Reduction of the average ambient temperature by 0.15 K
[203]	Antlanta/USA	0.15	0.30	Negligible
[203]	Atlanta/USA	0.15	0.45	2.5 K
[204]	Various Californian Cities	0.117–0.152	0.18–0.252	1.0 K
[204]	Various Californian Cities	0.117–0.152	0.199–0.374	2.0 K
[205]	Los Angeles, USA	0.13	0.26	3.0 K
[153]	Huston, USA	0.08 for pavements 0.1 for roofs 0.25 for walls	0.2 for pavements 0.3 for roofs 0.3 for walls	0.5 K
[206]	New York, USA	0.15	0.5	0.5 K
[151]	Los Angeles, USA	0.05 for pavements 0.15 for roofs	0.3 for pavements 0.5 for roofs	1.5 K
[152]	Various US cities		Increase of albedo of pavements by 0.15 and of roofs by 0.25	Decrease of the average ambient temperature by 0.11–0.53 K
[207]	Philadelphia, US		Increase of the global albedo by 0.1	Decrease of the average ambient temperature by 0.3–0.5 K

[152], has assumed that the albedo of roofs, walls and pavements increased from 0.1, 0.25 and 0.08 to 0.3, 0.3 and 0.2, respectively. It is reported that the average decrease of the ambient temperature ranges between 0.3 and 0.4 K, while the possible reduction of the peak ambient temperature may rise up to 3.5 K. Analysis of all existing data correlating the increase of the urban albedo against the potential decrease of the average ambient temperature, has shown that an albedo change of 0.1 in urban areas decreases the average ambient temperature by 0.3 K [47].

Few studies are available aiming to investigate separately the impact of cool pavements on the ambient temperature. In [153], the impact of various cool pavement technologies was evaluated for Fresno, USA. Two scenarios were investigated using the MIST software tool [154]. The so called realistic scenario considered that the city's albedo may increase by 0.02 because of the use of cool pavements. The considered strategies involved the use of micro-surfacing or white topping, chip seals, and high albedo paints. It is calculated that such an application may reduce the average ambient temperature of the city by 0.2 K. In parallel, the so called maximum scenario considered an increase of the city's albedo by 0.09 solely due to cool pavements. The same as above technologies were considered, but for a larger part of the city's pavement. It is calculated that such a scenario may decrease the average temperature of the city by 0.8 K. Another similar study for Tokyo, Japan, is reported in [75]. It is calculated that when cool pavements are considered for the central area of Tokyo, (16 km^2), the average ambient temperature may decrease by 0.15 K, while in certain areas the temperature reduction may rise up to 0.6 K.

4.4. Real applications and performance of reflective pavements

In parallel to the global studies aiming to investigate the potential of high albedo materials in cities, several smaller scale projects were carried out to optimize the rehabilitation of specific urban zones or design new urban areas. The characteristics of these small scale projects are presented in Table 3.

The study and the application of cool pavements in a dense urban area in Maroussi, Athens is described in [70]. The project dealt with the rehabilitation of a zone of 16,000 m^2, using new high reflectivity pavements, green spaces and earth to air heat exchangers. The existing paving surfaces consisted of black asphalt for roads and dark concrete tiles for pavements with albedo lower than 0.4. The area was extensively monitored and it was found that existing comfort conditions were not at the acceptable levels because of the high ambient and surface temperatures. All conventional asphalt was replaced by colored asphaltic material presenting a reflectivity close to 0.35 [102], while for the open spaces and pavements natural reflective materials, marbles, and concrete pavements colored with high reflectivity paints were used. The reflectivity of the marbles was 0.7 while the initial reflectivity of the colored concrete pavements was 0.78. Detailed CFD simulations were performed to evaluate the climatic potential of the employed bioclimatic techniques. It was calculated that the replacement of cool pavements may decrease the peak ambient temperature in the area by 1.2–2.0 K while the overall temperature decrease because of the application of all measures may rise up to 3.4 K. The project is actually under construction.

The use of cool pavements as part of a global bioclimatic rehabilitation of the public open spaces in Tirana, Albania is described in [72]. The surface of the rehabilitated urban area was close to 25,000 m^2. The overall design apart from the use of reflective pavements, involved the use of additional green spaces, solar control pergolas and extensive use of earth to air heat exchangers to provide cool air. The existing pavements were quite dark concrete or stone tiles installed in most of the open spaces. The albedo of the existing pavements was lower than 0.15–0.2. Monitoring of the area has shown that it was characterized by high ambient and surface temperatures during the summer period while comfort conditions were not of acceptable level. Pavement materials were replaced by new ones made of concrete and colored with infrared reflective paints. The albedo of the proposed tiles varied between 0.65 and 0.75 as a function of the tile's color. The climatic impact of the proposed mitigation measures was evaluated using advanced simulation techniques. It was estimated that the use of the proposed cool pavements contributes to decrease the peak ambient temperature by 2.1 K while the full depression of the peak ambient temperature because of all the proposed measures was close to 3 K. The project is actually under construction.

The bioclimatic rehabilitation of a highly populated area in the central zone of Athens, Greece is described in [69]. The project

Table 3
Existing projects where reflective pavements are applied.

Reference	City/country	Type of existing pavement	Type of new pavement	Surface of the area	Results
[70]	Maroussi, Athens, Greece	Black asphalt and concrete pavements with albedo lower than 0,4	Cool Asphalt in Roads with albedo close to 0.35. Natural Reflective materials for pavements, (marble), with albedo 0.7. Concrete pavements colored with infrared reflective cool paints with albedo 0.78.	16,000 m^2	Replacement of pavements decreases the average peak ambient temperature by 1.2–2.0 K.
[72]	Tirana/Albania	Black asphalt and dark concrete pavements with albedo lower than 0.2	Concrete pavements colored with infrared reflective cool paints with albedo between 0.65–0.75 depending on the color	25,000 m^2	Replacement of pavements decreases the average peak ambient temperature by 2.1 K
[69]	Athens/Greece	Concrete tiles initially of white color, (initial albedo=0.45). Black asphalt on roads	Use of photocatalytic asphalt on the roads. Concrete pavements colored with infrared reflective cool paints with albedo 0.68.	4160 m^2	Replacement of pavements decreases the average peak ambient temperature by 1.6 K. Decrease of the surface temperature of the pavements close to 4.5 K.
[71]	Faliron/Athens/ Greece	Asphalt concrete and dark paving materials. The albedo of the paved surfaces was between 0.35 and 0.45 while in areas covered by concrete and asphalt the albedo was lower than 0.2	Concrete pavements colored with infrared reflective cool paints with albedo 0.60.	4500 m^2	The use of cool paving materials reduces the peak ambient temperature during a typical summer day, by up to 1.9 K. The surface temperature in the park was decreased by 12 K.
[76]	Putrajaya, Malaysia	Not mentioned	Paving materials with albedo equal to 0.8	420,000 m^2	The global reduction of the temperature because of the implementation of trees and cool paving is 1.5 K. It seems that the contribution of cool pavements is close to 0.1 K.
[208]	St Thomas Square, Athens/ Greece	Dark concrete pavements	Concrete tiles colored with infrared reflective cool paints with albedo 0.60.	12,500 m^2	Not monitored
[208]	Faneromenis Av, Holargos, Greece	Dark concrete pavements	Photocatalytic concrete tiles colored with infrared reflective cool paints with albedo 0.60.	5000 m^2	Not monitored
[208]	Kostantopoulou Av, Kesariani, Greece	Dark concrete pavements	Concrete tiles colored with infrared reflective cool paints with albedo 0.50.	10,000 m^2	Not monitored
[208]	Ilion, Greece	Dark concrete pavements	Concrete tiles colored with infrared reflective cool paints with albedo 0.50.	2500 m^2	Not monitored

covers an area of 4160 m^2 and involves the use of cool pavements for streets and other open zones, additional greening, shading of open spaces and the use of earth to air heat exchangers. The existing pavements were black asphalt on the roads and white concrete tiles having an initial albedo of 0.45 in the rest of the open zones. Because of the use, the albedo of the tiles was decreased substantially. Monitoring of the area has taken place and it was concluded that ambient and surface temperatures were quite high while the use of proper mitigation techniques could substantially improve the environmental quality of the area. The overall bioclimatic rehabilitation plan involved the use of photocatalytic asphalt in the streets, the use of concrete tiles colored with infrared reflective paints, additional shading and green areas and use of earth to air heat exchangers. Simulation of the existing and the proposed situation under the average peak summer conditions has shown that the use of the cool pavements may decrease the average peak summer ambient temperature by 1.6 K while the average surface temperature of the pavements may decrease up to 4.5 K during the summer period.

The rehabilitation of an urban park in the major area of Athens, Greece, is described in [71]. The project is situated next to the cost and covers a total area of 4500 m^2. Before the rehabilitation the park was composed by asphalt, concrete and dark paving materials. The albedo of the paved surfaces was between 0.35 and 0.45 while in areas covered by concrete and asphalt the albedo was lower than 0.2. The area was monitored during the summer period and both ambient and surface temperatures found to be quite high and out of the acceptable comfort conditions. The rehabilitation plan of the project involved the excessive use of cool pavements together with the addition of green spaces. Concrete pavements colored with infrared reflective cool paints with albedo 0.60 were installed in the park area. The project has been extensively monitored after the end of the constructions and by using a combination of measurements and simulations, it was found that the achieved reduction of the average peak ambient temperature was close to 1.9 K, while the peak surface temperature in the area has been reduced by 12 K.

The results of a study aiming to investigate the mitigation potential of green spaces and cool pavements in Putrijaya, Malaysia is described in [76]. The study covers an area of 420,000 m^2 and considers that existing paving materials will be replaced by new ones having an albedo equal to 0.8. Simulations have been performed and it is found that both mitigation techniques contribute to decrease the ambient temperature by 1.5 K. From the given results, it can be concluded in an indirect way that the contribution of cool pavements was close to 0.1 K.

The application of cool concrete pavements in four large rehabilitation projects in Athens, Greece is reported in [155]. In all cases, concrete pavements colored with infrared reflective cool paints with albedo's between 0.50 and 0.60 were installed. The projects are not monitored and performance results are not available.

Reflective pavements present important advantages as reduce the surface temperature and the sensible heat flux to the atmosphere contributing to a more effective mitigation of urban heat island. Given that the reported results are performed under completely different climatic and operational conditions, it is impossible to perform any type of performance comparison.

As it concerns possible disadvantages of reflective pavements it should be mentioned that the reflected solar radiation may affect the thermal balance of pedestrians. The thermal sensation of human beings over reflective pavements is studied and analyzed in [156,157]. It is concluded that the increased radiation field creates some thermal comfort problems compared to the conventional pavements. As reported, the increase of the radiation flux of short wave radiation was almost the double than the reduction of the infrared radiation emitted by the surface caused by the decreased surface temperature.

5. Permeable pavements

Permeable and water retentive pavements generally include additional voids than conventional pavements in order to allow water to flow through into the sub-layers and the ground while may include water holding fillers to store water. Evaporation of the water helps to reduce the surface temperature of the pavements and contribute to the mitigation of the urban heat island while the risk of flooding is reduced. According to Takahashi Katsunori and Yabuta Kazuya [158], three are the performance criteria for water retentive pavements: (a) the ability to decrease its surface temperature under fine weather, (b) sustainability to suppress the temperature rise after rainfalls and (c) maximum durability and minimum decrease of its performance over time.

5.1. Existing development and commercial applications of water retentive pavements

Permeable and water retention pavements can be vegetated or not. An extensive presentation of water retentive pavements is given in [159]. A review of the main advantages and disadvantages of permeable pavements is given in [160].

Porous asphaltic pavements consists of fine and course stone aggregates bound by a bituminous-based binder and is mainly used to reduce storm water problems, reduce noise and also to mitigate when possible heat island from parking and other low traffic urban areas. Porous asphalt is a bituminous material bind together with aggregates and achieves its porosity by eliminating the fine particles from the mixture. It is composed by a top filter course which should be at minimum 5 cm thick and contain crushed aggregates of stone of 1.3 cm, a filter course, a storage course, geotextile filter fabric and the existing soil which should be permeable to the water [161,162]. According to Miklas Scholz_and Piotr Grabowiecki [160], the porous asphalt should be composed by open graded asphalt concrete with void spaces close 18%. The reflectivity of porous asphalt depends on the reflectivity of the individual materials used. In general the solar reflectance of porous pavements is lower than the reflectance of the equivalent non-porous solution. Evaporation in non-vegetated permeable and water retention pavements is highly influenced by the distribution of the particle size of the bedding material and by the retention of water in the blocks of the surface, [157,163].

Permeable concrete is produced using cement and cement supplementary materials like fly ash, ground blast furnace slag, pozzolans or silica fumes, aggregates and water. Porosity is achieved through three types of pores: Pores in the cement past, aggregate voids and air voids. The latter are the more important concerning the water permeability [158]. The final permeability of pervious concrete is mainly defined by the type of the binder used, the type of aggregate, the combination of the mix and the compaction and finally by the aggregate grading [164–170]. Values of water permeability typically vary between 20 and 40 mm/s, however smaller and higher values are reported [168,170,171].

Vegetative pavements consist mainly of interlocking units filled with grass and soil and planted at the top with grass. Such a pavement is permeable and allows water to flow through. Cooling of the surface is achieved by evaporation. Several studies have shown that the surface temperature of grass is quite lower than many other materials used for pavements [172–174]. Many industrial products presenting an increased durability of the pavements are available.

5.2. Current research direction on the field of permeable and water retensive pavements

Important research has been carried out to improve the thermal performance of permeable and water retentive pavements. Six technological approaches are developed and tested (Fig. 2) for asphalt, concrete and ceramic pavements. Table 4 reports the main characteristics and results of the six main current research directions. In particular:

(a) Use of water holding fillers made of steel by products as an additive to porous asphalt: In [175], a new water holding pavement consisted of water holding fillers made of steel by products and integrated in porous asphalt is presented and tested both experimentally and theoretically against porous asphalt used in permeable pavements with a porosity equal to 0.3. It is reported that the average surface temperature of the water holding pavement was 0.6 K lower than that of the infiltration porous asphalt, while the air temperature above the water holding pavement was almost 0.5 K lower than above the conventional porous asphalt. The sudden decrease of the surface temperature of the conventional porous asphalt was higher than that of the water holding pavement, however the evaporation and the cooling effect in the later continue for longer than the conventional porous pavement presenting a maximum of about 3 days.

(b) Use of fine blast-furnace powder in water retentive asphalt. The development and testing of a water retentive pavement material for roads using fine blast-furnace powder is described in [158]. The fine blast furnace powder is an admixture used in cement and like and is generated by the blast furnace process. The material was tested experimentally under real conditions in roads for long periods and it is shown that the water absorbing properties of the material present only a small change after accelerated curing, while as it concerns its thermal performance it is reported that during the third year of its operation, its surface temperature was even 14 K lower that of a dense graded asphalt pavement.

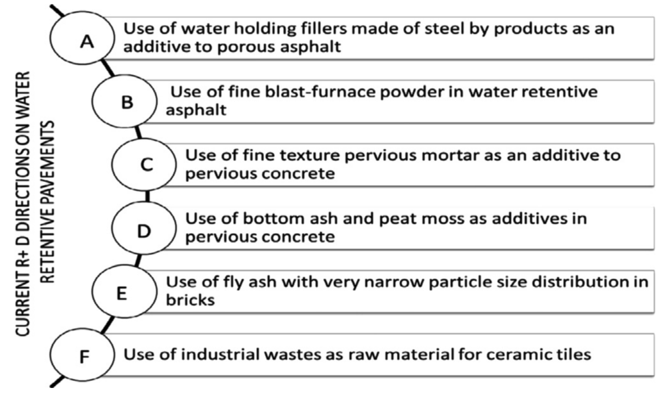

Fig. 2. Current research priorities on the field of permeable and water retentive pavements.

Table 4
Description of the existing technological trends on the field of permeable and water retentive pavements.

No.	Description of the technology	Type of pavement	Thermal performance	Reference
1.	Use of water holding fillers made of steel by products as an additive to porous asphalt	Asphalt	The average surface temperature of the water holding pavement was 0.6 K lower than that of the infiltration porous asphalt	[159]
2.	Use of fine blast-furnace powder in water retentive asphalt	Asphalt	Its surface temperature was 14 K lower that of a dense graded asphalt pavement	[160]
3.	Use of fine texture pervious mortar as an additive to pervious concrete	Concrete	Data are not available	[161]
4.	Use of bottom ash and peat moss as additives in pervious concrete	Concrete	It presents almost 18 K lower surface temperature than asphalt after a rainfall, while the maximum surface temperature difference with the conventional porous pavement was almost 9 K	[171]
5.	Use of fly ash with very narrow particle size distribution in bricks	Ceramic	Decrease of the surface temperature by several degrees.	[172,173]
6.	Use of industrial wastes as raw material for ceramic tiles	Ceramic	Its surface temperature was almost 10 K lower than that of the dry material and almost 25 K cooler than the surface temperature of conventional asphalt	[174]

Table 5
Main research priorities other than reflective and permeable pavements.

No.	Description of the technology	Thermal performance of the pavements	Reference
1.	Use of phase change materials in the mass of the pavement	Compared to the tiles colored with conventional pigments, the temperature depression of the PCM doped pavement was 2.9–8.3 K. Compared to the tiles with infrared reflective pigments the temperature decrease was 0.6–2.6 K	[35]
2.	Circulation of water in the mass of asphaltic pavements	The surface temperature of the pavement may decrease up to 4–5 K as a function of the circulated mass of water	[127,128,148,197–201]
3.	Use of photovoltaic pavements	The surface temperature of photovoltaic pavements may be 3–5 K lower than that of conventional concrete pavements	Unpublished Work

(c) Use of fine texture pervious mortar as an additive to pervious concrete: The development and testing of a pervious concrete pavement combined with fine texture pervious mortar is described in [164]. Mortar is produced using cementitious materials, aggregate and water and is used in order to improve the surface texture of the pervious concrete. The water permeability of the final composition was quite low, (2–3 mm/s). No data are available about the thermal performance of the new material.

(d) Use of bottom ash and peat moss as additives in pervious concrete: The development and the experimental evaluation of a novel porous pavement block using bottom ash and peat moss is described in [176]. Peat is a porous material that acts as an adsorbent to remove heavy metals from aqueous solutions. The developed pavement was tested experimentally against conventional asphalt and normal porous blocks. It is found that the proposed material presents almost 18 K lower surface temperature than asphalt after a rainfall, while the maximum surface temperature difference with the conventional porous pavement was almost 9 K.

(e) Use of fly ash with very narrow particle size distribution in bricks: The development of porous bricks presenting an open porosity of 22–43% is reported in [177]. The bricks have an average porous size between 0.4 and 50 μm and were prepared using fly ash with very narrow particle size distribution. Experimental work reported in [178], has shown that lower surface temperatures of water retentive materials in association to the limited reflected radiation helps to improve thermal comfort of citizens.

(f) Use of industrial wastes as raw material for ceramic tiles: In [179], a new water retentive ceramic tile used for pavement has been developed and experimentally tested. The tile is made using industrial wastes as raw material and is considered as one of the most water retentive ones. The pavement has been experimentally tested outdoors under saturation conditions and is found to be almost 10 K of lower temperature than a concrete roof. In parallel, the air above the tile was almost 1–2 K of lower temperature. The use of water retentive materials presenting a high capillary ability has been proposed in [180]. As reported, these materials have the ability to suck up and spread efficiently the water in the whole surface of the pavement. Measurements have shown that the surface temperature of the proposed materials was almost 10 K lower than that of the dry material and almost 25 K cooler than the surface temperature of conventional asphalt. The measured sensible and latent heat fluxes from the wet material were 70 W/m^2 and 430 W/m^2 respectively.

5.3. *Experimental testing and thermal performance of permeable and water retensive pavements*

Several studies have been performed aiming to test the thermal performance of permeable and water retentive pavements. Five experimental works are reported in the literature comparing the thermal performance of various types of permeable and water retentive pavements against conventional ones. The main characteristics of the experimental comparisons and the obtained results are reported in Table 5. The main conclusion drawn from the comparative evaluation of the five experimental works is that the performance of the permeable pavements depends highly on their design characteristics as well as on the boundary conditions where the experiments taken place. In most of the cases the results are quite contradictory. For example in [181], it is found that permeable concrete presented higher surface temperatures than the conventional concrete pavement, however in [182], it is found that permeable pavements presented almost 4 K of lower surface temperature than the conventional ones. In parallel, comparisons performed between the surface temperature of permeable pavements and asphaltic materials show that permeable materials present either a lower temperature [121,183], or both temperatures were almost similar [184], or the temperature

of the permeable pavement was even higher than that of the asphalt [185]. A short presentation of the comparative experimental works is given below.

The thermal performance of pervious concrete pavements has been compared against traditional concrete pavements in [185], using both experimental and theoretical techniques. It is reported that pervious concrete presented higher surface temperatures during the daytime while during the night, both surface temperatures were of the same order. It is also found that less energy was stored in pervious concrete while, for similar cement mixtures, had a lower solar reflection than conventional cement pavements. Similar results are reported in [184–186]. In all cases pervious concrete had higher surface temperatures compared against traditional concrete pavements, however its temperature decreased rapidly under the concrete pavement.

The thermal performance of various types of pavements has been evaluated experimentally in [183]. Tested pavements involved porous blocks, asphalt, grass and ceramic surfaces. It is reported that during noon the maximum surface temperature of the porous block was 54.8 °C and was similar to the surface temperature of the asphalt. In parallel, the surface temperature of the ceramic pavement and of the grass was close to 44 °C. Even at early morning (06:00), a surface temperature difference of 3.0 K was observed between the two blocks of pavements (porous block and asphalt against grass and ceramic). For all the materials the maximum temperature was measured at 20 cm below the surface of the pavement while it was found that the subsurface heat storage is higher for the porous block and the asphalt than for the grass and the ceramic pavement. It is noted that the reflectivity of the tested materials were: 0.25 for the porous block, 0.08 for the asphalt, 0.27 for the grass and 0.24 for the ceramic pavement. It is also mentioned that during the experiment, the surface of the porous block was dry and so, no evaporation losses taken place.

In [172], the thermal performance of 16 different pavements including conventional, porous and water retaining asphalt, concrete and interclocking materials, is tested both experimentally and theoretically. In parallel, for comparison reasons, grass and bare soils have been tested. It is reported that the pavements presenting the lowest and higher temperatures were the grass and the conventional asphalt, with a maximum temperature difference of 20 K and 4 K during the day and the night period. The reduction of the sensible heat flux during the day and night against conventional asphalt has been estimated for all types of pavements. The daytime sensible heat reduction of bare soil was 270 W/m^2 and 350 W/m^2 for grass. The corresponding sensible heat reduction for the interlocking and the cement pavements were 280 and 180 W/m^2 respectively. As it concerns the so called 'cool pavements', the sensible heat reduction of the porous and water retaining concrete was close to 100 W/m^2, compared to the sensible heat of the conventional asphalt, while the corresponding reduction of the water retaining asphalt was around 140 W/m^2.

In [121], the performance of 15 permeable and water retentive concrete pavements was tested experimentally. Among the tested pavements, 4 were permeable and 11 were non-permeable. The overall experimental testing has shown that there is no correlation between the surface temperature and the permeability of the water retentive concrete blocks. As it concerns the surface temperature of the tested pavements it is reported that the water retentive concrete blocks presented a much lower surface temperature than a dense grade asphalt pavement. In particular when the asphalt pavement had 56.1 °C, the surface temperature of the water retentive blocks was 7.2–16.6 K lower ranging between 38.5 and 48.9 °C. Additionally, it was found that water retentive pavements presenting a lower surface temperature after the rain, had also a lower temperature 8 days after. Similar results are presented in [182], where the water retention capability of porous pavements has been experimentally tested.

The thermal performance of pervious pavements is experimentally tested and reported in [188]. It is found that pervious pavements presented almost 4.1 K lower surface temperature than the corresponding conventional pavement, while during the night period the difference was close to 1.0 K.

Water retentive pavements are mainly used in hot and humid climates where water availability is not a problem. The application of these pavements has gained a very increased acceptance in countries like USA, China, Australia, UK and Japan. Applications are also performed in Northern countries and in particular in parking lots where during the summer the surface temperature of the asphalt was slightly higher while surface temperatures above 20 °C, were presented 12% more often than in the concrete pavements. Most of the large scale projects were designed and implemented aiming to manage storm water problems and also to mitigate heat island and deal with the design and rehabilitation of parking lots, streets and pavements. Additional information on large scale applications of water retentive pavements can be collected from [77]. Unfortunately, most of the projects are not monitored, and information on the specific performance of the projects is not available and thus it is not possible to evaluate the details of the applications.

5.4. Water availability and alternative techniques

Permeable and water retentive pavements require important quantities of water in order to perform in a proper way. In hot and humid climates, rain water is mainly used to enhance evaporation in the pavement system. However, for less rainy climates reclaimed or waste water, when available, may be used instead.

The idea to sprinkle reclaimed water on water retentive pavements in order to increase evaporation and decrease its surface temperature has been extensively investigated in Japan [189–191]. In all cases, it is observed that by sprinkling water on roads made from water retentive materials reduce substantially their surface temperature. Laboratory experiments reported in [192,193] where the evaporation efficiency of water retentive pavements was measured have shown that the surface temperature of these materials depends strongly on their water retention and evaporation efficiency. It is suggested that a water supply system is necessary in order to achieve the lowest possible surface temperatures. A large scale experimental application in open spaces, where reclaimed wastewater was sprinkled on water retentive pavements is described in [172]. The experiment was carried out in Shiodome District on Tokyo, Japan. It is reported that water has decreased the road surface temperature by 8.0 K during the day and 3.0 K during the night period. In particular, during the daytime the surface temperature of the area sprinkled with water was 37.8 °C against 45.8 °C of the zone without sprinkling of water. The corresponding nighttime period surface temperatures were 28.8 °C and 31.8 °C respectively. In case sprinkling happened only during the daytime, it was observed that the water retentive pavement had a lower surface temperature even during the next night. In parallel, the sensible heat losses were estimated and it was found that water sprinkling lowers the sensible flux by almost 30%. In particular, the sensible flux in the sprinkled and non-sprinkled areas during the day period were close to 154 kJ/m^2 and 456 kJ/m^2 respectively, while during the nighttime the corresponding fluxes were 16 and 62 kJ/m^2

6. Other technologies

Apart of the reflective and water retentive pavements, other techniques were explored both theoretically and experimentally.

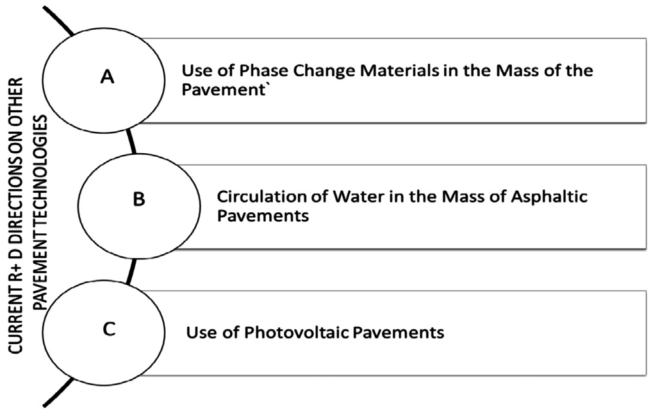

Fig. 3. Current research priorities on other cool pavement technologies.

Three main research directions are proposed and investigated (Fig. 3) Table 5 summarizes the characteristics of the proposed techniques.

(a) *Use of phase change materials in the mass of the pavement*: Increase of the thermal capacitance of the paving materials contributes to decrease surface temperatures and the amount of sensible heat released to the atmosphere. The use of phase change materials into the mass of pavements aiming to increase the heat stored under the form of latent heat is proposed in [35]. Phase change materials have been extensively tested to decrease peak temperatures in buildings and amortize peak cooling loads [188–196]. In particular, different color paving tiles have been prepared using infrared reflective pigments together with nano-phase change materials of different concentrations and melting temperatures. The PCM doped tiles have been experimentally compared against tiles of the same color made with the use of the same infrared reflective pigments but without phase change materials and tiles prepared with conventional color pigments. Testing under hot summer conditions has shown that the PCM doped tiles presented significantly lower temperatures. Compared to the tiles colored with conventional pigments, the temperature depression was of the order of 2.9–8.3 K, while compared to the tiles prepared with infrared reflective pigments the achieved temperature decrease was between 0.6 and 2.6 K. Temperature differences were observed mainly in the morning hours (07:00–10:00), when the phase change material melts. During the rest of the day and night, the impact of the PCM was not important and the surface temperature of the tile prepared with infrared reflective pigments was almost the same. In parallel, it is reported that the concentration of PCM in the mass of the paving material is not significant after a certain concentration value, while the melting point temperature of the doping materials defines the time period when the tiles exhibit lower temperatures. The study has concluded that PCM doping materials help to decrease the surface temperature of paving materials, however the relative impact and contribution is not spectacular.

(b) *Circulation of water in the mass of asphaltic pavements*: The idea to cool asphalt by circulating water through pipes placed behind its surface has been investigated by many authors [127,128,148,199–202]. Given the very high surface temperature of the asphalt during the summer period, circulation of water could decrease the temperature in the body and the surface of the asphalt pavement and reduce the sensible heat convection to the atmosphere. Water may be pumped up from an underground storage medium, a river or any other source. The warm water can be used for the generation of electricity by using thermoelectric equipment or simply used as warm water. It is obvious that the efficiency of the proposed system depends highly on the location and spacing of the pipes. Experiments and simulations carried out show that the thermal potential of the system is quite high, however several problems have to be overcome. In particular, the low thermal conductivity of asphalt reduces the heat transfer through the pavement, the problems of maintenance because of the pressure on the pipes, and other structural and practical issues and problems arising from the use of an extensive piping system, have to be resolved. The system was applied in several real scale projects in the Netherlands [128].

(c) *Use of photovoltaic pavements*: The use of photovoltaics as pavements was investigated recently. New technologies for photovoltaic pavements based on the use of PV tiles made with glass integrated over ceramic, enables walking on and placing of furniture. Photovoltaic pavements may provide electricity, save space and in case their surface temperature is appropriate, they could contribute to mitigate heat islands in cities. Preliminary results obtained during the summer of 2012 in Athens has shown that the surface temperature of photovoltaic pavements may be 3–5 K lower than that of conventional concrete pavements.

7. Conclusions

Important research is carried out aiming to better document, understand and mitigate urban heat islands. New materials, systems and technologies have been developed and proposed in order to decrease the sensible heat flux to the atmosphere from different urban structures like buildings and paved surfaces. Business around pavements present an extreme commercial importance and employ hundreds thousands of workers, engineers and administrators. It is during the very recent years that researcher working on pavement technologies started to look on their optical and thermal properties and the possible impact on urban climate.

As it concerns the research objectives on the field of cool pavements, two main research streams have been developed aiming either to develop highly reflective paved surfaces or permeable pavements making use of the cooling evaporation capacity of water. Research on shading devices and vegetative pavements has offered some very interesting architectural proposals, however the technical developments on these fields are quite limited. Other proposed techniques and technologies mainly based on the use of mechanical systems are of marginal importance for the time being.

Actual research trends to develop highly reflective pavements focus on the the use of highly reflective white coatings and infrared reflective colored pigments to increase the albedo of the pavements surface, the use of reflective paints to increase the reflectance of the pavement ingredients, and also the use of color changing paints to achieve a better thermal performance all year round. Laboratory tests have shown that the albedo achieved can be very high and the pick surface temperature of the paved materials may decrease by up to 20 K. Newly developed reflective materials and techniques were tested in many demonstration and real scale projects. Unfortunately, few projects are monitored in detail to document precisely the expected benefits from a large scale implementation of reflective pavements. It is considered that there is an urgent need for more large scale demonstration projects to assess experimentally and in detail all aspects related

to the modification of the local microclimate and the possible impact on thermal comfort and energy consumption.

Permeable and water retentive pavements, vegetated or not, are more appropriate for rainy and humid areas where the availability of water is not a problem. Actual research targets aim mainly to involve additional agents in the mass of the pavements like steel bioproducts, fine blast furnace powder, fine texture pervious mortar, bottom and fly ash, peat moss and industrial wastes. Research aims also to improve the capillary ability of the pavements to increase the water content and the evaporation capacity of the materials. Laboratory tests have shown that new generation permeable pavements seem to present a significant lower surface temperature than the corresponding conventional permeable materials. However, the thermal performance of the permeable and water retentive pavements depends highly on the availability of water.

Many demonstration and large scale applications of permeable and water retentive pavements have been realized. However, the existing scientific information regarding their thermal performance is quite limited, as very few projects have been monitored. Uncontestably, important developments have been realized mainly on the laboratory level, however it is widely accepted that research on cool pavements has to progress faster and more concrete achievements have to be.

References

[1] James and James (Science) 2001.
[2] Santamouris M. Heat island research in Europe The state of the art. Advances in Building Energy Research 2007;1:123–50.
[3] Akbari H, Davis S, Dorsano S, Huang J, Winert S. Cooling our communitiesda guidebook on tree planting and white coloured surfacing. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division; 1992.
[4] Giannopoulou K, Livada I, Santamouris M, Saliari M, Assimakopoulos M, Caouris YG. On the characteristics of the summer urban heat island in Athens, Greeve. Journal of Sustainable Cities and Society 2011;1:16–28.
[5] Founda D. Evolution of the air temperature in Athens and evidence of climatic change: a review. Journal of Advances in Building Energy Research 2011;5(1):7–41.
[6] Asimakopoulos D, Santamouris M, Farrou I, Laskari M, Saliari M, Zanis G. Modelling the energy demand projection of the building sector in Greece in the 21st century. Energy and Buildings 2012;49:488–98.
[7] Livada I, Santamouris M, Assimakopoulos MN. On the variability of summer air temperature during the last 28 years in Athens. Journal of Geophysical Research 2007;112:D12103.
[8] Mihalakakou G, Flocas HA, Santamouris M, Helmis CG. Application of neural networks to the simulation of the heat island over Athens, Greece, using synoptic types as a predictor. Journal of Applied Meteorology 2002;41:5519–27.
[9] Gobakis K, Kolokotsa D, Synnefa A, Saliari M, Giannopoulou K, Santamouris M. Development of a model for urban heat island prediction using neural network techniques. Sustainable Cities and Society 2011;1(2):104–15.
[10] Mihalakakou G, Santamouris M, Papanikolaou N, Cartalis C, Tsangrassoulis A. Simulation of the urban heat island phenomenon in Mediterranean climates. Journal of Pure and Applied Geophysics 2004;161:429–51.
[11] Livada I, Santamouris M, Niachou K, Papanikolaou N, Mihalakakou G. Determination of places in the great Athens area where the heat island effect is observed. Theoretical and Applied Climatolology 2002;71:219–30.
[12] Pantavou K, Theoharatos G, Mavrakis A, Santamouris M. Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens. Building and Environment 2011:46.
[13] Sakka A, Santamouris M, Livada I, Nicol F, Wilson M. On the thermal performance of low income housing during heat waves. Energy and Buildings 2012;49:69–77.
[14] Cleveland C. Heat Island. Encyclopedia of Earth 2007.
[15] Ashley Erin, Lemay, Lionel, Concrete's contribution to sustainable development. Available at: 〈http://www.specifyconcrete.org/assets/docs/Concretes_Contribution_to_Sustainable_Development.pdf〉.
[16] Hassid S, Santamouris M, Papanikolaou N, Linardi A, Klitsikas N, Georgakis C, et al. The effect of the Athens heat island on air conditioning load. Journal of Energy and Buildings 2000;32:2131–41.
[17] Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, et al. On the impact of urban climate to the energy consumption of buildings. Solar Energy 2001;70:3201–16.
[18] Cartalis C, Synodinou A, Proedrou M, Tsangrassoulis A, Santamouris M. Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region. Journal of Energy Conversion and Management 2001;42(14):1647–56.
[19] Hirano Y, Fujita T. Evaluation of the impact of the urban heat island on residential and commercial energy consumption in Tokyo. Energy 2012;37(1): 371–83.
[20] Taha H, Akbari H, Rosenfeld A, Huang J. Residential cooling loads and the urban heat island—the effects of albedo. Building and Environment 1988;23(4): 271–283.
[21] Kolokotroni M, Giannitsaris I, Watkins R. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. Solar Energy 2006;80(4):383–92.
[22] Fung WY, Lam KS, Hung WT, Pang SW, Lee YL. Impact of urban temperature on energy consumption of Hong Kong. Energy 2006;31(14):2287–301.
[23] Davies M, Steadman P, Oreszczyn T. Strategies for the modification of the urban climate and the consequent impact on building energy use. Energy Policy 2008;36(12):4548–51.
[24] Stathopoulou E, Mihalakakou G, Santamouris M, Bagiorgas HS. Impact of temperature on tropospheric ozone concentration levels in urban environments. Journal of Earth System Science 2008;117(3):227–36.
[25] Santamouris M, Paraponiaris K, Mihalakakou G. Estimating the ecological footprint of the heat island effect over Athens, Greece. Climate Change 2007;80:265–76.
[26] Sarrat C, Lemonsu A, Masson V, Guedalia D. Impact of urban heat island on regional atmospheric pollution. Atmospheric Environment 2006;40:1743–58.
[27] Santamouris M, Pavlou K, Synnefa A, Niachou K, Kolokotsa D. Récent progress on passive cooling techniques. Advanced technological developments to improve survivability levels in low e income households. Energy and Buildings 2007;39:859–66.
[28] Kolokotsa D, Maravelaki-Kalaitzaki P, Papantoniou S, Vangeloglou E, Saliari M, Karlessi T, et al. Development and analysis of mineral based coatings for buildings and urban structures. Solar Energy 2012;86(5):1648–59.
[29] Synnefa, Saliari M, Santamouris M. Experimental and numerical assessment of the impact of increased roof reflectance on a school building in Athens. Energy and Buildings 2012; 55:7–15.
[30] Synnefa A, Dandou M, Santamouris M, Tombrou N. Soulakellis: use of cool materials as a heat island mitigation strategy. Journal of Applied Meteorology and Climatology 2008;47(11):2846–56.
[31] Synnefa A, Santamouris M, Akbari H. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. Energy and Buildings 2007;39(11):1167–74.
[32] Rosenfeld AH, Akbari H, Bretz S, Fishman BL, Kurn DM, Sailor D, et al. Mitigation of urban heat islands: materials, utility programs, updates. Energy and Buildings 1995;22(3):255–65.
[33] Rosenfeld AH, Akbari H, Romm JJ, Pomerantz M. Cool communities: strategies for heat island mitigation and smog reduction. Energy and Buildings 1998;28(1):51–62.
[34] Karlessi T, Santamouris M, Apostolakis K, Synnefa A, Livada I. Development and testing of thermochromic coatings for buildings and urban structures. Solar Energy 2009;83(4):538–51.
[35] Karlessi T, Santamouris M, Synnefa A, Assimakopoulos D, Didaskalopoulos P, Apostolakis K. Development and testing of PCM doped cool colored coatings to mitigate urban heat island and cool buildings. Building and Environment 2011;46(3):570–6.
[36] Ma Y, Zhu B, Wu K. Preparation and solar reflectance spectra of chameleon-type building coatings. Journal of Solar Energy 2001;70:417–22.
[37] Ma Y, Zhang X, Zhu B, Wu K. Research on reversible effects and mechanism between the energy-absorbing and energy-reflecting states of chameleon-type building coatings. Journal of Solar Energy 2002;72:511–20.
[38] Yu Chen Hien, Nyuk Wong. Thermal impact of strategic landscaping in cities: a review. Advances in Building Energy Research 2009;3(1):237–60.
[39] Julia E, Santamouris M, Dimoudi A. Monitoring the effect of urban green areas on the heat island in Athens. Environmental Monitoring and Assessment 2009;156(1–4):275–92.
[40] Mihalakakou G, Santamouris M, Asimakopoulos D. On the use of ground for heat dissipation. Journal of Energy 1994;19(1):17–25.
[41] Tzaferis A, Liparakis D, Santamouris M, Argiriou A. Analysis of the accuracy and sensitivity of eight models to predict the performance of earth to air heat exchangers. Journal of Energy and Buildings 1992;18:35–43.
[42] Santamouris M, Sfakianaki A, Pavlou K. On the efficiency of night ventilation techniques applied to residential buildings. Energy and Buildings 2010;42: 1309–13.
[43] Geros V, Santamouris M, Tsangrassoulis A, Guarracino G. Experimental evaluation of night ventilation phenomena. Journal of Energy and Buildings 1999;29:141–54.
[44] Geros V, Santamouris M, Karatasou S, Tsangrassoulis A, Papanikolaou N. On the cooling potential of night ventilation techniques in the urban environment. Energy and Buildings 2005;37:243–57.
[45] Kusaka H, Kimura F, Hirakuchi H, Mizutori M. The effects of land-use alteration on the sea breeze and daytime heat island in the Tokyo metropolitan area. Journal of the Meteorological Society of Japan 2000;78(4): 405–20.
[46] Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy 2001;70 (3):295–310.
[47] Akbari H. Shade trees reduce building energy use and CO_2 emissions from power plants. Environmental Pollution 2002;116(1):S119–26.

[48] Santamouris M. Cooling the cities—a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy 2012 [in press].
[49] Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. Journal of Energy and Buildings 2001;33:719–29.
[50] Santamouris M, Pavlou C, Doukas P, Mihalakakou G, Synnefa A, Hatzibiros A, et al. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. Energy 2007;32(9):1781–8.
[51] Sfakianaki E, Pagalou K, Pavlou M, Santamouris MN. Assimakopoulos: theoretical and experimental analysis of the thermal behaviour of a green roof system installed in two residential buildings in Athens, Greece. International Journal of Energy Research 2009;33(12):1059–69.
[52] Zinzi M. Cool materials and cool roofs: potentialities in Mediterranean buildings. Advances in Building Energy Research 2010;4(1):201–66.
[53] Theodosiou T. Green roofs in buildings: thermal and environmental behaviour. Advances in Building Energy Research 2009;3(1):271–88.
[54] Takebayashi H, Moriyama Masakazu. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. Building and Environment 2007;42:2971–9.
[55] Synnefa A, Santamouris M. Advances on technical, policy and market aspects of cool roof technology in Europe: The Cool Roofs project. Energy and Buildings 2012;55:35–41.
[56] Savio P, Rosenzweig Cynthia, Solecki William D, Slosberg Ronald B. Mitigating New York City's Heat Island with Urban Forestry, Living Roofs, and Light Surfaces. New York City Regional Heat Island Initiative. Albany, NY: The New York State Energy Research and Development Authority; 2006.
[57] Sailor D. Simulated urban climate response to modifications in surface albedo and vegetative cover. Journal of Applied Meteorology 1995;34: 1694–700.
[58] Rosenzweig C, Solecki W, Parshall L, Gaffin S, Lynn B, Goldberg R, et al. Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. Preprints, Sixth symposium on the urban environment, Atlanta, GA: American Meteorological Society; J3.2., 2006 [Available online at ⟨http://www.giss.nasa.gov/research/news/20060130/103341.pdf⟩].
[59] Menon S, Akbari Hashem, Mahanama Sarith, Sednev Igor, Levinson Ronnen. Radiative forcing and temperature response to changes in urban albedos and associated CO_2 offsets. Environmental Research Letters 2010;5:014005.
[60] Gaitani N, Michalakakou G, Santamouris M. On the use of bioclimatic architecture principles in order to improve thermal comfort conditions in outdoor spaces. Building and Environment 2007;42(1):317–24.
[61] Rose LS, Akbari H, Taha H. Characterizing the fabric of the urban environment: a case study of greater Houston, Texas. Paper LBNL-51448. Berkeley, CA: Lawrence Berkeley National Laboratory; 2003.
[62] Akbari H, Rose LS. Characterizing the fabric of the urban environment: a case study of metropolitan Chicago, Illinois. Paper LBNL-49275. Berkeley, CA: Lawrence Berkeley National Laboratory; 2001.
[63] Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy 2001;70(3): 295–310.
[64] Akbari H, Rose LS, Taha H. Characterizing the fabric of the urban environment: a case study of Sacramento, California. Paper LBNL-44688. Berkeley, CA: Lawrence Berkeley National Laboratory; 1999.
[65] Gray K, Finster M. The urban heat island, photochemical smog, and Chicago: local features of the problem and solution, 2000. Evanston, IL: Department of Civil Engineering Northwestern University, US Environmental Protection Agency.
[66] Parking infrastructure: energy, emissions, and automobile life-cycle environmental accounting; July 29, 2010 [stacks.iop.org/ERL/5/034001].
[67] AASHTO, Rough roads ahead. American Association of State Highway and Transportation Officials, Washington, DC; 2010.
[68] Tran Nam, Powell Buzz, Marks Howard, West Randy, Kvasnak Andrea. Strategies for design and construction of high-reflectance asphalt pavements, transportation research record. Journal of the Transportation Research Board 2009:124–30, http://dx.doi.org/10.3141/2098-13 No. 2098, Transportation Research Board of the National Academies, Washington, DC.
[69] Gaitani N, Spanou A, Saliari M, Synnefa A, Vassilakopoulou K, Papadopoulou K, et al. Improving the microclimate in urban areas: a case study in the centre of Athens. Journal of Building Services Engineering 2011;32(1):53–71.
[70] Santamouris M, Xirafi F, Gaitani N, Spanou A, Saliari M, Vassilakopoulou K. Improving the microclimate in a dense urban area using experimental and theoretical techniques. The case of Marousi, Athens. International Journal of Ventilation 2012;11(1):1–16.
[71] Santamouris M, Gaitani N, Spanou A, Saliari M, Gianopoulou K, Vasilakopoulou K. Using cool paving materials to improve microclimate of urban areas—design realisation and results of the Flisvos project. Building and Environment 2012;53:128–36.
[72] Fintikakis N, Gaitani N, Santamouris M, Assimakopoulos M, Assimakopoulos DN, Fintikaki M, et al. Bioclimatic design of open public spaces in the historic centre of Tirana, Albania. Sustainable Cities and Society 2011;1(1):54–62.
[73] Sugie Lee a, Steven P. French : Regional impervious surface estimation: an urban heat island application. Journal of Environmental Planning and Management 2009;52(4):477–96.
[74] Dave Yates PE, Marjorie Melton PECO. City of St. Louis permeable pavement alley pilot study. Conference proceedings paper. World environmental and water resources congress; 2009.
[75] Toshiya Takahashi, Challenge for cool city Tokyo, Osaka. GSEP workshop; 2011
[76] Shahidan MF, Jones PJ, Gwilliam J, Salleh E. An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials. Building and Environment 2012;58:245–57.
[77] Environmental Protection Agency, EPA: Heat island effect, heat island mitigation, initiative types by state & locality; 2012. Available at: ⟨http://www.epa.gov/heatisld/images/extra/level3_pavingproducts.html⟩.
[78] Torbjörn Gustavsson Jörgen Bogren, Green Cecilia. Road climate in cities: a study of the Stockholm Area, South-East Sweden. Meteorological Applications 2001;8:481–9.
[79] Asaeda T, Thanh Ca Vu, Wake Akio. Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment 1996;30(3):413–27.
[80] Doll D, Ching JKS, Kaneshiro J. Parameterizion ation of subsurface heating for soil and concrete using net radiation data. Boundary-Layer Meteorology 1985;32:351–72.
[81] Golden JS, Kaloush KE. Mesoscale and microscale evaluation of surface pavement impacts on the urban heat island effects. International Journal of Pavement Engineering 2006;7(1):37–52.
[82] Barring L, Mattson J, Lindqvist S. Canyon geometry, street temperatures and urban heat island in Malmo, Sweden. Journal of Climatolology 1985;5: 433–44.
[83] Quattrochi DA, Ridd MK. Measurement and analysis of thermal energy responses from discrete urban surfaces using remote sensing data. International Journal of Remote Sensing 1994;15(10):1991–2022.
[84] Streutker DR. A remote sensing study of the urban heat island of Houston, Texas. International Journal of Remote Sensing 2002;23:2595–608.
[85] Streutker DR. Satellite-measured growth of the urban heat island of Houston, Texas. Remote Sensing of Environment 2003;85:282–9.
[86] Carnahan WH, Larson RC. An analysis of an urban heat sink. Remote Sensing of Environment 1990;33:65–71.
[87] Voogt JA, Oke TR. Complete urban surface temperatures. Journal of Applied Meteorology 1997;36(9):1117–32.
[88] Roth M, Oke TR, Emery WJ. Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. International Journal of Remote Sensing 1989;10:1699–720.
[89] Buettner K, Kern D. The determination of infrared emissivities of terrestrial surfaces. Journal of Geophysical Research 1965;70:1329–37.
[90] Combs AC, Weickmann HK, Mader C, Tebo A. Application of infrared radiometers to meteorology. Journal of Applied Meteorology 1965;4:253–62.
[91] Rubio E, Caselles V, Coll C, Valour E, Sospedra F. Thermal infrared emissivities of natural surfaces: improvements on the experimental set-up and new measurements. International Journal of Remote Sensing 2003;24:5379–90.
[92] Qin Yinghong, Hiller Jacob E. Modeling temperature distribution in rigid pavement slabs: impact of air temperature. Construction and Building Materials 2001;25:3753–61.
[93] Solaimanian M, Kennedy TW. Predicting maximum pavement surface temperature using maximum air temperature and hourly solar radiation. Transport Research Record: Journal of Transportation Research Board 1993;1417:1–11.
[94] Ramadhan RH, Al-Abdul Wahhab HI. Temperature variation of flexible and rigid pavements in Eastern Saudi Arabia. Building and Environment 1997;32(4): 367–73.
[95] Bentz DP. A computer model to predict the surface temperature and time-of wetness of concrete pavements and bridge decks. National Institute of Standards and Technology, NISTIR 6551; 2000.
[96] Gui J, et al. Impact of pavement thermophysical properties on surface temperatures. Journal of Materials in Civil Engineering 2007;19(8): 683–90.
[97] Yavuzturk C, Ksaibati K, Chiasson AD. Assessment of temperature fluctuations in asphalt pavements due to thermal environmental conditions using a two dimensional, transient finite-difference approach. Journal of Materials in Civil Engineering 2005;17(4):465–75.
[98] Hermansson Ake. Mathematical model for paved surface summer and winter temperature: comparison of calculated and measured temperatures. Cold Regions Science and Technology 2004;40:1–17.
[99] Gavin_Gui Jooseng, Phelan Patrick E, Kaloush Kamil E, Golden Jay S. Impact of Pavement thermophysical properties on surface temperatures. Journal of Materials in Civil Engineering 2007;19:8.
[100] Santamouris M, editor. Energy and climate in the urban built environment. London: James and James (Science); 2001.
[101] Doulos L, Santamouris M, Livada I. Passive cooling of outdoor urban spaces. The role of materials. Solar Energy 2004;77(2):231–49.
[102] Synnefa A, Karlessi T, Gaitani N, Santamouris M, Assimakopoulos DN, Papakatsikas C. On the optical and thermal performance of cool colored thin layer asphalt used to improve urban microclimate and reduce the energy consumption of buildings. Building and Environment 2011;46(1):38–44.
[103] Niachou K, Livada I, Santamouris M. Experimental study of temperature and airflow distribution inside an urban street canyon during hot summer weather conditions. Part 1. Air and surface temperatures. Journal of Building and Environment 2008;43(8):1383–92.
[104] Georgakis Ch, Santamouris M. Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes. Energy and Buildings 2006;38(4):367–76.
[105] Berg R, Quinn W. Use of light colored surface to reduce seasonal thaw penetration beneath embankments on permafrost. In: Proceedings of the

second international symposium on cold regions engineering. University of Alaska; 1978. p. 86–99.
[106] Taha H, Sailor D, Akbari H. High albedo materials for reducing cooling energy use. Lawrence Berkeley Laboratory Report 31721, UC-350, Berkeley, CA; 1992.
[107] Sthathopoulou M, Synnefa A, Cartalis C, Santamouris M, Karlessi T, Akbari H. A surface heat island study of Athens using high-resolution satellite imagery and measurements of the optical and thermal properties of commonly used building and paving materials. Journal of Sustainable Energy 2009;28(1–3):59–76.
[108] Pomerantz M, Akbari H, Chen A, Taha H, Rosenfeld AH. Paving materials for heat island mitigation, LBL-3 8074. The work was supported by the U.S. Environmental Protection Agency, and by the Office of Energy Efficiency and Renewable Energy, Office of Building Technologies, of the U.S. Department of Energy under Contract no. DE-ACO3-76SFooo98. Heat Island Project, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720. U.S. Department of Energy, Washington, DC 20585, November 1997.
[109] Synnefa A, Santamouris M, Livada I. A study of the thermal performance of reflective coatings for the urban environment. Solar Energy 2006;80(8): 968–81.
[110] Shi Zhiyang, Zhang Xiong. Analyzing the effect of the longwave emissivity and solar reflectance of building envelopes on energy-saving in buildings in various climates. Solar Energy 2011;85(1):28–37.
[111] Gui J, Phelan P, Kaloush K, Golden J. Impact of pavement thermophysical properties on surface temperatures. Journal of Materials in Civil Engineering 2007;19(8):683–90.
[112] Oke TR, Johnson GT, Steyn DG, Watson ID. Simulation of surface urban heat islands under 'ideal conditions at night—Part 2: diagnosis and causation. Boundary Layer Meteorology 1991;56:339–58.
[113] Jiji LM. Heat convection. 2nd ed Berlin, Heidelberg: Springer; 543.
[114] Çengel Y. Heat transfer. A practical approach, vol. 83, 2nd ed. New York: McGraw-Hill; 2003p. 368–75, and 578.
[115] Chung Y, Shin H-C. Characteristics of coefficient of thermal expansion of PCC pavement. In: Transportation research record 2009 annual meeting CD-ROM. Washington, DC: National Academy Council; 2008.
[116] Kim K-H, et al. An experimental study on thermal conductivity of cocrete. Cement and Concrete Research 2003;33(3):363–71.
[117] Khan MI. Factors affecting the thermal properties of concrete and applicability of its prediction models. Building and Environment 2002;37(6): 607–14.
[118] Hermansson A. Mathematical model for calculation of pavement temperatures: comparison of calculated and measured temperatures. Transportation Research Record, vol. 1764 TRB. Washington, DC: National Research Council; 180–188 paper no. 01-3543.
[119] Yamagata H, Nasu M, Yoshizawa M, Miyamoto A, Minamiyama M. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water Science and Technology 2008;57(5):763–71.
[120] Haselbach, Liv. Pervious concrete and mitigation of the urban heat island effect. Transportation Research Board 88th annual meeting, 2009-1-11 to 2009-1-15.
[121] Karasawa K, Toriiminami N, Ezumi K. Kamaya: Evaluation of performance of water-retentive concrete block pavements. In: 8th International conference on concrete block paving; 2006.
[122] Cool pavement report. EPA cool pavements study—Task 5, prepared for heat island reduction initiative. U.S. Environmental Protection Agency, prepared by Cambridge Systematics, Inc.; 2005.
[123] Tran Nam, Powell Buzz. Strategies for design and construction of high-reflectance asphalt pavements. NCAT report 09-02; 2009.
[124] Reducing urban heat islands: compendium of strategies cool pavements. Available at: 〈http://www.epa.gov/hiri/resources/pdf/CoolPavesCompendium.pdf〉.
[125] Cool pavements research and technology. Requested by Bruce Rymer, Office of Pavements Engineering, Prepared by Kendra K. Levine, Institute of Transportation Studies Library at UC Berkeley, September 1, 2011.
[126] Hunt William F., Collins Kelly A. Urban waterways, permeable pavement: research update and design implications North Carolina, USA: North Carolina Cooperative Extension Service; 2008.
[127] Mallick Rajib B., Chen Bao-Liang, Bhowmick Sankha. Reduction of urban heat island effect through harvest of heat energy from asphalt pavements. In: Proceedings of the heat island conference, LBNL; 2009.
[128] de Bondt AH, Jansen ing R. Generation and saving of energy via asphalt pavement surfaces Fachbeitrag in OIB—de Bondt; 2006. Available at: 〈http://www.roadenergysystems.nl/pdf/Fachbeitrag%20in%20OIB%20 %20de%20Bondt%20-%20English%20version%2013-11-2006.pdf〉.
[129] Akbari Hashem, Matthews, H.Damon. Global cooling updates: reflective roofs and pavements. Energy and Buildings 2012;55:2–6.
[130] Pomerantz M, Pon B, Akbari H, Chang SC The effects of pavement temperatures on air temperatures in large cities. Berkeley, CA: Heat Island Group, Lawrence Berkeley National Laboratory, LBNL-43442;2000.
[131] O'Leary, Bill. Heat island abatement & chip seal surface treatments. Available at: 〈http://files.harc.edu/Projects/CoolHouston/Meetings/20030710ChipSealTreatments.pdf〉.
[132] Hunter RN, editor. Bituminous mixtures in road construction. London: Thomas Telford Ltd; 1994.
[133] American Concrete Pavement Association (ACPA), R&T. Concrete pavement research & technology, June 2002, Web 12 May 2010. Available at: 〈http://www.acpa.org/Downloads/RT/RT3.05.pdf〉.
[134] Sultana, Sharmin. Extending asphalt pavement life with thin white topping [Thesis]. Manhattan, Kansas: Master of Science, Department of Civil Engineering, College of Engineering, Kansas State University; 2010.
[135] Sheehan, M.J., S. M. Tarr, and S., Tayabji, Instrumentation and field testing of thin white topping pavement in colorado and revision of the existing colorado thin white topping procedure. Report no. CDOT-DTD-R-2004-12. Denver: Colorado Department of Transportation Research Branch; 2004.
[136] Santamouris M, Synnefa A, Karlessi T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. Solar Energy 2011;85:3085–102.
[137] Santamouris M, Synnefa A, Kolokotsa D, Dimitriou V, Apostolakis K. Passive cooling of the built environment—use of innovative reflective materials to fight heat island and decrease cooling needs. International Journal Low Carbon Technologies 2008;3(2):71–82.
[138] Levinson R, Akbari H, Reilly JC. Cooler tile-roofed buildings with near-infrared-reflective non-white coatings. Building and Environment 2007;42 (7):2591–605.
[139] Levinson R, Akbari H, Berdahl P, Wood B, Skilton W, Petersheim J. A novel technique for the production of cool colored concrete tile and asphalt shingle roofing products. Solar Energy Materials and Solar Cells 2010;94(6):946–54.
[140] Synnefa A, Santamouris M, Apostolakis K. On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy 2007;81:488–97.
[141] Kinouchi T, Yoshinaka T, Fukae N, Kanda M. Development of cool pavement with dark colored high albedo coating. In: Fifth conference for the urban environment; 2004.
[142] Wan WC, Hien WN, Ping TP, Aloysius AJW. A study on the effectiveness of heat mitigating pavement coatings in Singapore. In: Second international conference on countermeasures to urban heat islands; 2009.
[143] Nishioka Masatoshi, Nabeshima Minako, Wakama Satoshi, Ueda Junya. Effects of surface temperature reduction and thermal environment on high albedo coating asphalt pavement. Journal of Heat Island Institute International 2006;1.
[144] Kondo Yasushi, Ogasawara Takeshi, Kanamori Hiroshi. Field measurements and heat budget analysis on sensible heat flux from pavements. Journal of Environmental Engineering, AIJ 2008;73(628):791–7.
[145] John Belkovitz. Can nanotechnology in concrete improve our roadways ? In: Emerald cities sustainability conference; 2011.
[146] Levinson, R. Cool pavements for cool communities. In: Emerald cities sustainability conference; 2011.
[147] Levinson, Ronnen. Solar reflectivity testing of Emerald cool pavement. Lawrence Berkeley National Laboratory.
[148] Boriboonsomsin Kanok, Reza Farhad. Mix design and benefit evaluation of high solar reflectance concrete for pavements. Transportation Research Record0361-1981 2011:11–20.
[149] Kawakami Atsushi, Kubo Kazuyuki. Development of a cool pavement for mitigating the urban heat island effect in Japan. In: 1st International symposium on asphalt pavements and environment. Zurich, Switzerland: International Society for Asphalt Pavements; 2008.
[150] van Bijsterveld WT, de Bondt AH. Structural aspects of pavement heating and cooling systems. In: 3rd International symposium on finite elements; 2002.
[151] Rosenfeld AH, Akbari Hashem, Romm Joseph J, Pomerantz Melvin. Cool communities: strategies for heat island mitigation and smog reduction. Energy and Buildings 1998;28:51–62.
[152] Millstein D, Menon, Surabi. Regional climate consequences of large-scale cool roof and photovoltaic array deployment. Environmental Research Letters 2011;6:034001.
[153] Taha H. Meso-urban meteorological and photochemical modelling of heat island mitigation. Atmospheric Environment 2008;42(38):8795–809.
[154] Fang Kevin, Cook Jon, Smith Jeremy, Williams Keisha: Reductions in ground-level ozone pollution through urban heat 1. Island mitigation strategies including rehabbing land occupied for transportation related uses: case study of Fresno, CA, 90th annual meeting of the Transportation Research Board. 6 Transportation and Air Quality (ADC20).
[155] Sailor D, Dietsch N. The urban heat island mitigation impact screening tool (MIST). 19, 2005. Available at: 〈http://www.heatislandmitigationtool.com/Introduction.aspx〉.
[156] Nakaohukubo Kazuaki, Hoyano Akira. Numerical analysis of radiant environment of outdoor living space considering the influence of spatial form and material. Journal of Environmental Engineering, AIJ 2008;73(630):957–64.
[157] Kondo Yasushi, Ogasawara Takeshi, Udoh Kunihiro. Influence of radiation reflected by cool pavement on thermal sensation of pedestrians. Journal of Environmental Engineering, AIJ 2009;74(637):323–30.
[158] Katsunori Takahashi, Kazuya Yabuta. Road temperature mitigation effect of "road cool," a Water-retentive material using blast furnace slag. JFE Technical Report, No. 13, May 2009.
[159] Ferguson Bruce K. Porous pavements. London, UK: Taylor and Francis; 2005.
[160] Scholz Miklas, Grabowiecki Piotr. Review of permeable pavement systems. Building and Environment 2007;42:3830–6.
[161] Jackson, N. Design, Construction and maintenance guide for porous asphalt pavements: information series 131. National Asphalt Pavement Association; 2003.
[162] Briggs JF. Performance assessment of porous asphalt for storm water treatment, Master of Science. University of New Hampshire; 2006.
[163] Andersen CT, Foster IDL, Pratt CJ. The role of urban surfaces (permeable pavements) in regulating drainage and evaporation: development of a laboratory simulation experiment. Hydrological Processing 1999;13:597–609.

[164] Aoki Yukari. Development of pervious concrete. Master of Engineering. University of Technology, Sydney Faculty of Engineering and Information Technology; 2009.
[165] Zouaghi A, Kumagai M. Adaptability of porous concrete to the environment. A monthly report of the Civil Engineering Research Institute For Cold Region; 2000: no. 566. p. 11–24.
[166] Yang J, Jiang G. Experimental study on properties of pervious concrete pavement materials. Cement and Concrete Research 2002;3:381–6.
[167] Haselbach LM, Freeman RM. Vertical porosity distributions in pervious concrete pavement. ACI Materials Journal 2006;103(6):7.
[168] Zhuge Y. A review of permeable concrete and its application to pavements. Mechanics and Structures and Materials 2006:601–7.
[169] Ghafoori N, Dutta S. Laboratory investigation of compacted no-fines concrete for paving materials. Journal of Materials in Civil Engineering 1995;7(3): 183–91.
[170] Haselbach LM, Valavala S, Montes F. Permeability predictions for sand clogged Portland cement pervious concrete pavement systems. Journal of Environmental Management 2006;81(1):42–9.
[171] Matsuo Y, Morino K, Iwatsuki E. A study of porous concrete using electric arc furnace oxidizing slag aggregate. Research report of Aichi Institute of Technology; 2005. p. 8.
[172] Yamagata H, Nasu M, Yoshizawa M, Miyamoto A, Minamiyama M. Heat island mitigation using water retentive pavement sprinkled with reclaimed wastewater. Water Science & Technology—WST 2008;57:5.
[173] Takebayashi Hideki, Moriyama Masakazu. Study on surface heat budget of various pavements for urban heat island mitigation. Advances in Materials Science and Engineering 2012. http://dx.doi.org/10.1155/2012/523051. Article ID 523051, 11 pages.
[174] Herb William R, Janke Ben, Mohseni Omid, Stefan Heinz G. Ground surface temperature simulation for different land covers. Journal of Hydrology 2008;356(3–4):327–43.
[175] Nakayama Tadanobu, Fujita Tsuyoshi. Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landscape and Urban Planning 2010;96:57–67.
[176] Jong-Bin Park, Jung-Hun Lee, Hee-Bum Pyun, Chae-SungGee ,Lee, Sangho: Novel porous pavement blocks for urban rainwater management and non-point source pollution control. Available at: ⟨http://www.iwahq.org/contentsuite/upload/iwa/Document/P06.pdf⟩.
[177] Yokota Kozo, Yamajiand Tsuyoshi, Hirano Shinichi. Basic characteristics of water permeable/retainable porous paving bricks for controlling urban heat island phenomenon. Journal of Heat Island Institute International 2010:5.
[178] Hiroyuki Akagawa, Takebayashi Hideki, Moriyama Masakazu. Experimental study on improvement on human thermal environment on a watered pavement and a highly reflective pavement. Journal of Enviromental Engineering AIJ 2008;73(623):85–91.
[179] Ozaki Tetsuji, Suzuki Yoshinori. Study on the contribution of water-retentive ceramic tile to the reduction of environment heat accumulation. Journal of Hydraulic Engineering 1998:42.
[180] Hiroyuki Akagawa, Hidetaka Komiya. Experimental study on pavement system with continuous wet surface. Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ) 2000;530:79–85.
[181] Yilmaz H, Toy S, Irmak M, Yilmaz S, Bulut Y. Determination of temperature differences between asphalt, concrete, soil and grass surfaces of the city of Erzurum, Turkey. Athmosphera 2008;21(2):135–46.
[182] Hoyano Akira, Marui Motofumi, Matsumoto Akiriho, Asawa Takashi. A study of pavement body configurations of the evaporative cooling pavement system with a focus on rainwater retention and capillary absorption through a summer outdoor experiment. Journal of Heat Island Institute International 2011:6.
[183] Asaeda Takashi, Ca Vu Thanh. Characteristics of permeable pavement during hot summer weather and impact on the thermal environment. Building and Environment 2000;35:363–75.
[184] Kevern John T, Schaefer Vernon R. Temperature response in a pervious concrete system designed for stormwater treatment. Geotechnical special publication, (178). p. 1137–44.
[185] Kevern John T., Haselbach Liv, Schaefer Vernon R. Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems. In: Second international conference on countermeasures to urban heat islands; 2009.
[186] Haselbach L., Gaither A.Preliminary field testing: urban heat island impacts and pervious concrete. In: Proceedings of NRMCA 2008 concrete technology forum: focus on sustainable development; 2008 [CD-ROM].
[188] Satoshi Nishiyama, Yuzo Ohnishi, Takao Yano. Study on the effect of permeable pavement on improvement of heat environment in urban area. Journal of Heat Island Institute International 2007:2.
[189] Kinouchi T, Kanda M, Kuriki M, Kobayashi H. An observation of the climatic effect of watering on paved roads. In: Proceedings of the Hydraulic Engineering, JSCE; 1994. 38, p. 381–386 [in Japanese].
[190] Minegishi J, Kobayashi K, Takeda T. Durability and road properties of road temperature decrease function of water absorptive pavement. Annual Report I.C.E. of TMG 2004. 2004. p. 75–86.
[191] Ashikari Y, Hamada T, Ikeda M, Kitada S, Yanagisawa T, Fujiwara H. Practical study on the effect of the environment-conscious pavement. In: Proceedings of 34th annual meeting of environmental systems research 2005, 2005. p. 421–5.
[192] Kinoshita S, Yoshida A, Okuno N. Evaporation performance analysis for water retentive material based on outdoor heat budget and transport properties. In: The 2nd international conference on countermeasures to urban heat islands; 2009.
[193] Misaka Ikusei, Narita, Ken-ichi, Yokoyama, Hitoshi. Evaluation of evaporation ability of the system for mitigating urban heat island. In: The seventh international conference on urban climate.
[194] Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: state of the art and outlook. Building and Environment 2007;42:2197–209.
[195] Tyagi V, Buddhi D. PCM thermal storage in buildings: a state of art. Renewable and Sustainable Energy Reviews 2007;11:1146–66.
[196] Xu X, Zhang Y, Lin K, Di H, Yang R. Modeling and simulation on the thermal performance of shape stabilized phase change material floor used in passive solar buildings. Energy and Buildings 2005;37:1084–91.
[197] Pasupathy A, Velraj R, Seeniraj R. Phase change material-based building architecture for thermal management in residential and commercial establishments. Renewable and Sustainable Energy Reviews 2008;12:39–64.
[198] Kissock JK, Hamming JM, Whitney TI, Drake ML. Testing and simulation of phase change wallboard for thermal storage in buildings. In: Proceedings of the international solar energy conference; 1998. p. 45–52.
[199] Hasebe MY, Kamikawa S. Meiarashi thermoelectric generators using solar thermal energy in heated road pavement. In: Proceedings of ICT '06. 25th international conference on thermoelectric; 2006. p. 697–700.
[200] Kinouchi T, Yoshinaka T, Fukae N, Kanda M. Development of cool pavement with dark colored high albedo coating. In: 5th Symposium on the urban environment; 2004. p. 207–10.
[201] Bijsterveld WT, van LJM, Houben A, Scarpas3, Molenaar AAA. Effect of using pavement as solar collector on pavement temperature and structural response. Journal of Transportation Research Board, No. 1778, Transportation Research Board, National Research Council, Washington, DC, 2001.
[202] Wayne Lee Kang-Won, Correia Andrew J. A pilot study for investigation of novel methods to harvest solar energy from asphalt pavements. A final report for Korea Institute of Construction Technology (KICT); 2010.
[203] Slag cement smoothes out Detroit metro airport terminal expansion. Available at: ⟨http://www.slagcement.org/News/Story_DetroitMetroAirport.html⟩.
[204] IEC: green parking lot case study: Heifer International Inc. 2007. Available at: ⟨http://www.epa.gov/region6/6sf/pdffiles/heiferparkingstudy.pdf⟩.
[205] EPA design/construction of a permeable pavement demonstration site at the Edison Environmental Center. Available at: ⟨www.epa.gov⟩.
[206] Zhou Yan ZJ, Shepherd Marshall. Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. Natural Hazards 2010;52:639–68, http://dx.doi.org/10.1007/s11069-009- 9406-z.
[207] Taha H. Urban surface modification as a potential ozone air quality improvement strategy in California: a mesoscale modeling study. Boundary-Layer Meteorology 2008;127:219–39, http://dx.doi.org/10.1007/s10546-007-9259-5.
[208] ABOLIN: cool construction materials. Presentation of success stories, October 2010, Athens, Greece.